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SIGNIFICANCE OF INCLOSED MEANDERS IN THE PHYSIOGRAPHIC HISTORY OF THE COLORADO PLATEAU COUNTRY[1]

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ABSTRACT

If meanders formed in the latter part of an erosion cycle are intrenched in immediately subjacent hard rocks without change of plan when uplift rejuvenates the stream, but are greatly changed or lost in the process of deepening the valley in weak rocks, present distribution of meanders indicates the character of the rocks through which the stream has cut since the beginning of the present cycle of erosion. Construction of a restored geological section along a stream course permits determination, by empirical vertical shifting of the stream profile, of a single position in which meanders at the selected elevation will be preserved by intrenchment in hard rocks, where intrenched meanders actually occur, and will be lost by cutting downward through a considerable thickness of soft rocks, where intrenched meanders are absent. This observation, checked by a fairly close accordance of results obtained by independent study of different streams and peneplain remnants in the Colorado Plateau, indicates that the relative elevation of stream valleys in the earlier erosion cycle may be approximately determined from study of inclosed meanders.

INTRODUCTION

In a recent paper[2] the writer has presented observations on the geographic plan and topographic form of stream valleys in the Colorado Plateau country, and has discussed their origin. Attention has been drawn particularly to the meandering canyons, many

[1] Published by permission of the Director of the United States Geological Survey.

[2] Raymond C. Moore, "Origin of Inclosed Meanders on Streams of the Colorado Plateau," *Journal of Geology*, Vol. XXXIV (1926), pp. 29–57.

of which seem clearly to have been formed by intrenchment of meanders developed on flood plains in a former well-advanced erosion cycle, in certain cases with no appreciable modification of the pattern of the inherited meanders, in others with more or less lateral shifting due to side-cutting during downward corrasion. On smaller streams are "ingrown" meanders in hard rocks, the narrow canyons showing prominent slip-off slopes on the spurs that project into meander bends and strongly undercut cliffs on the outer and downstream sides of the bends; in soft rocks these streams have open valleys and relatively straight, wide, shallow channels. This paper describes additional features of the valleys and undertakes to ascertain their significance with respect to the physiographic history of the region.

GENERAL OBSERVATIONS

Beginning with the intrepid explorations of John Wesley Powell, a large body of scientific observations concerning the Colorado Plateau country and bearing on its geologic history has been gathered. It is not our purpose, nor is it desirable, to review here the contributions of the many different workers in this field, but a brief statement, at least, of general facts and their interpretation is a necessary introduction to study of the physiographic history of this region, a subject that has come to be known as "the plateau problem."

Relation of drainage to rock structure.—From the standpoint of geologic structure, the position of Colorado River and its tributaries is in many places anomalous. The peculiar course of Green River directly across, rather than around, the Uinta Mountains uplift, of the Yampa across Junction Mountain, of the San Juan, Paria, and other Colorado tributaries across pronounced monoclinal folds, and finally, of Colorado River across the Grand Canyon upwarp, not to mention lesser structural features—all these have long been pointed out as evidence either that the streams are older than the structures that are thus crossed, or that the streams were superposed upon these structural features. It was the view of Powell and most of the older geologists that Colorado River and many of its tributaries were antecedent streams which cut their valleys across structural barriers

as these were slowly upraised. It is now evident that much of the deformation of the rocks in the plateau country, the effects of which are so signally ignored by the position of the major stream courses, took place at the close of the Cretaceous or beginning of the Tertiary, almost surely long before the Colorado drainage had come into existence. Accordingly, the independence of the streams as regards structure appears assignable to superposition. After the deformation mentioned above, erosion planed off the country to a more or less even surface on which in Eocene time fresh-water sediments, and, in places, younger rocks, were deposited widely. The Colorado and its main tributaries appear to have been established on these Tertiary sediments, and as the Tertiary beds were eroded, to have been let down on whatever older rocks chanced to underlie the Tertiary in different places. Probably a considerable share of the stripping of Mesozoic strata from the Grand Canyon dome, which authors have attributed to a former erosion cycle of the Colorado, the so-called "Great Denudation," was accomplished before the time of Eocene deposition by streams which had no relation to present drainage.

Peneplain remnants.—In several parts of the plateau country remnants of old erosion surfaces, some of them beveling smoothly hard and soft rocks alike, are found. These occur at different elevations, and are mostly found, as might be expected, at considerable distances from the main drainage lines where, in the present cycle of canyon-cutting, erosion has been most profound. It has not been possible satisfactorily to correlate these so-called peneplain remnants, chiefly because the remnants are not sufficiently large or sufficiently studied, and because it is in most cases impossible, in a region of alternating hard and soft, nearly flat-lying rocks, to discriminate true peneplain remnants from subhorizontal areas of stripped hard rocks developed in the present cycle. Differential elevation of the plateau country through warping and faulting, a possible large regional relief at the time of maximum development of the erosion surface, and other factors add to difficulties. These remnants indicate clearly that at least one well-advanced erosion cycle preceded the present cycle of very active downcutting.

Inclosed meanders.—The rather intricate meanders of many

streams in the Colorado Plateau have been noted by several observers who conclude that the intrenchment of the meanders in deep canyons is the normal result of rejuvenation of erosive activity by the regional uplift that inaugurated the present physiographic cycle. The modifications of meanders by lateral cutting during downward corrasion, and particularly the significance of absence of meanders in many parts of the streams that show meanders in others, has not been specially noted; nor has attention been directed to the peculiar distribution of meandering canyons along minor streams, and the possible origin of these in the present erosion cycle. It is primarily the object of this paper to apply conclusions that have been advanced by the writer as to origin of these inclosed meanders in certain places, and absence of meanders in others, to interpretation of physiographic history.

INCLOSED MEANDERS ON SAN JUAN RIVER

One of the first places which the writer had opportunity to study in this geologically and scenically most interesting region was the section of remarkable inclosed meanders on San Juan River, near Goodridge, Utah (Fig. 1). The significance of these meanders, and especially their localization on certain parts of San Juan River, has ever since been an alluring subject of inquiry. Supplemented by observations on the occurrence of inclosed meanders on minor streams in other parts of southern Utah, and aided by the excellent detailed geologic description of the San Juan Canyon by Miser,[1] the characters distinguishing the lower course of this river have been the inception of the present study.

Bluff to Chinle Creek.—Near the town of Bluff and extending approximately ten miles southwestward to the prominent upturned wall of sandstone known as Comb Ridge, San Juan River is a very broad, very shallow, stream. Although in dry weather much of the channel is a sandy flat, it is in places three-quarters of a mile from one bank to another. With the exception of one minor swing to the south, the river's course is relatively straight. This part of the San

[1] Hugh D. Miser, "Geologic Structure of San Juan Canyon and Adjacent Country, Utah," *U. S. Geol. Survey Bull. 751 D*, 1924; "The San Juan Canyon, Southeastern Utah," *U.S. Geol. Survey Water Supply Paper 738*, 1924.

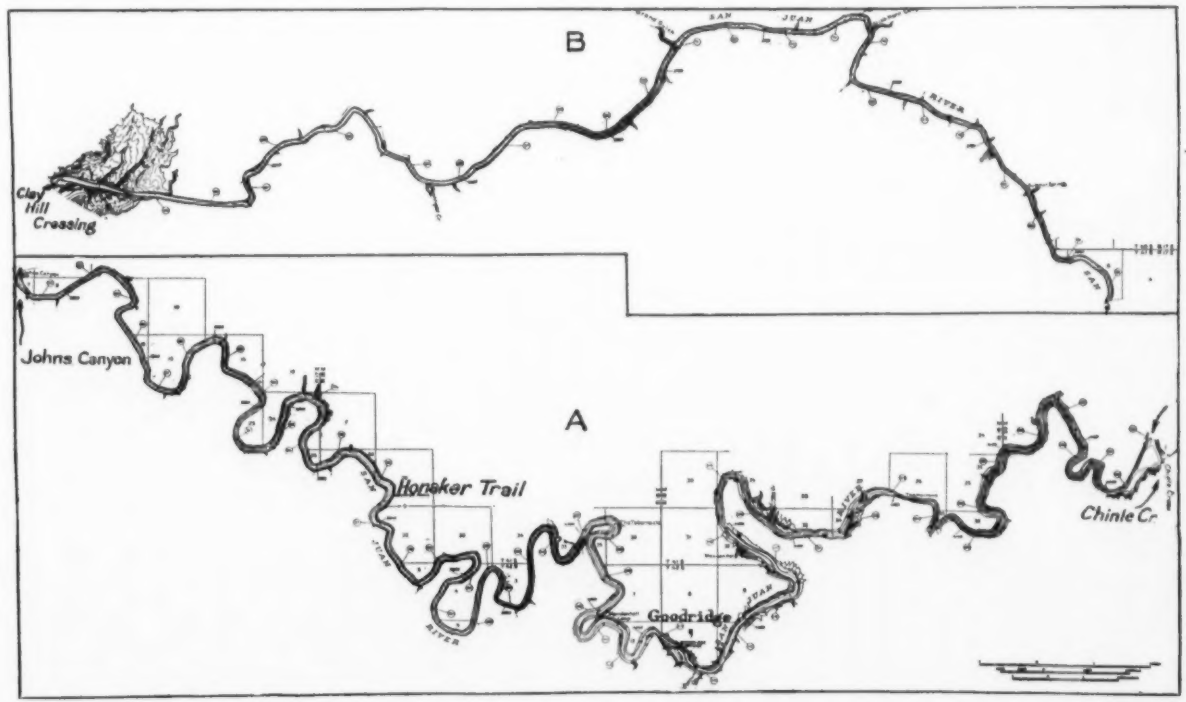

FIG. 1.—Map of San Juan River, Utah. (*A*) Chinle Creek to Johns Canyon; (*B*) Johns Canyon to Clay Hill Crossing. Contours below 3,900 feet, *United States Geological Survey.*

Juan Valley is carved mainly in relatively weak rocks as compared with those next downstream, and accordingly it is broad and the characters of the stream and its valley represent the features developed by erosion in soft rocks. If this portion of the river's course had formerly a distinctly meandering pattern, as for reasons offered presently it presumably did, all traces of this meandering pattern have been effectively obliterated. The barrier of hard Carboniferous limestone below Chinle Creek has doubtless been effective in retarding downcutting farther upstream, and lateral erosion has given the main character of the valley.

Chinle Creek to Johns Canyon.—On crossing the sandstone portal of Comb Ridge and passing the mouth of Chinle Creek, San Juan River encounters uplifted hard older rocks (Coconino ?,[1] Supai ?), and Goodridge, in which there are two major anticlines with an intervening syncline. The highest portion of the anticlinal uplift occurs some 15 miles west of Comb Ridge, but the river flows in these uplifted older rocks for a distance of more than 75 miles. In the eastern half of this rock belt, that is, between Chinle Creek and Johns Canyon, the course of San Juan River is notably meandering, but west of Johns Canyon there are only minor irregularities in the river's course. The maximum depth of the meandering canyon, from the rim rock at the top of the Goodridge formation to the river, is about 1,340 feet, measured at and near Honaker trail below Goodridge. The ends of the projecting spurs which extend into the meander bends are comparable in steepness to the slopes on the outer or concave side of the bends.[2] There is no evidence of the development of slip-off slopes, and we may assume, accordingly, that these meanders have been intrenched in a normal manner from meanders belonging to an earlier cycle of erosion. The position of this ancestral San Juan must have been here at least 1,300 or 1,400 feet above the present stream as defined by the intrenched canyon. However, unless the old San Juan, whose meanders are now so deeply intrenched, had a position much higher above the present stream than the top of the inner canyon walls, that is, about 1,350

[1] In the writer's opinion, the sandstone mapped as Coconino in recent reports on southeastern Utah is not strictly identical with the typical Coconino.

[2] See Fig. 8, p. 42, this *Journal*.

feet near Honaker trail, there were nearby cliffs rising several hundred feet above the river flood-plain. Cedar Point, a spur of the Coconino (?) Plateau north of the river, rises 2,000 feet above the bottom of the canyon only a little over a mile away. Sandstone cliffs on the south side of the San Juan are about four miles distant. Therefore, either intrenchment during the present cycle has been greater than 1,350 feet in this region, or there existed, at the time of the graded old San Juan, nearby cliffs that bordered its valley. The latter condition is not at all inharmonious with an advanced stage of erosion in an arid region, but it is not in accord with the common concept of a peneplain. To the north the plateau rises to almost 7,000 feet above sea-level on Elk Ridge, and at many places elsewhere in the vicinity of the San Juan there are elevations of 6,000 feet or more. Navajo Mountain, only a few miles south of the lower part of the San Juan and very near Colorado River, has an elevation of 10,416 feet. Certainly these highlands long antedate the beginning of the canyon cycle on the San Juan, though they did not have their present elevations formerly.

In places the meander belt of the San Juan canyon is bordered on each side by a sandstone plateau (Coconino?) rising some 800 feet above the top of the Goodridge. The distribution of this plateau seems correlated in an interesting manner with the inferred erosion plane of an earlier cycle, for where it rises appreciably above the assumed level of the ancient San Juan the cliffs have receded a considerable distance from the river, as clearly shown on the geologic map of the district[1]

Johns Canyon to Great Bend.—If the inclosed meanders in the section between Chinle Creek and Johns Canyon indicate the rejuvenation and deep intrenchment of a former meandering stream, the very different nature of the stream course below Johns Canyon is of special interest and must be considered (Fig. 1). A geological section along San Juan River (Fig. 3) shows that before reaching the hard Coconino (?) and Goodridge formations in which this part of the river is now carved, a considerable thickness of soft rocks must have been removed by the river in lowering its valley from the elevation represented by the intrenched meanders upstream to the present

[1] H. D. Miser, *loc. cit.*

level. If the effects of active corrasion in soft rocks which have been discussed in the writer's earlier paper obtain here, there might be expected a measurable loss of the intricately meandering pattern which presumably characterized the stream at the stage preceding uplift, and by the time the hard rocks which underlie the soft had been reached, the partially straightened river was let down into the hard rocks with a very different pattern from that which, in the upstream section, was preserved, because hard rocks immediately underlay the old erosion surface there.

For a short space in the vicinity of Clay Hill Crossing and again near Zahns Camp, just below the mouth of Copper Creek (Fig. 2), downward erosion from the former erosion level to the present must have been almost altogether in soft rocks (Fig. 3). The river now flows in a broad valley whose sides consist of bad-land slopes, and it spreads in a wide channel with a maximum width of 3,300 feet.[1] The stream course is somewhat irregular, but not meandering, and the position of the main flow shifts frequently. Miser[2] reports that during a flood while he was encamped on this part of the river in 1921 the channel was widened fully 75 feet by cutting the bank near camp. The water is very heavily charged with sediment.

Between the Clay Hill Crossing and Zahns Camp, and from the latter to a point below Spencer Camp east of Great Bend, meanders developed at a stage when the river was some 1,500 feet higher than now in this place would have been incised for some distance in sandstones of the Navajo, Todilto, and Wingate formations, and in these rocks the meander pattern should have been retained more or less faithfully. On reaching the underlying softer rocks (Chinle, Moenkopi) the valley must have increased in width gradually, though probably following in the main the general pattern of the original meanders, until the sandstone retaining walls had retreated sufficiently to permit what appears to be the normal tendency in weaker rocks under conditions of active downward corrasion—the modification and partial obliteration of a strongly meandering pattern. The meanders of the section here under dis-

[1] H. D. Miser, "The San Juan Canyon, Southeastern Utah," *U.S. Geol. Survey Water Supply Paper 538* (1924), p. 11.

[2] *Loc. cit.*, p. 50.

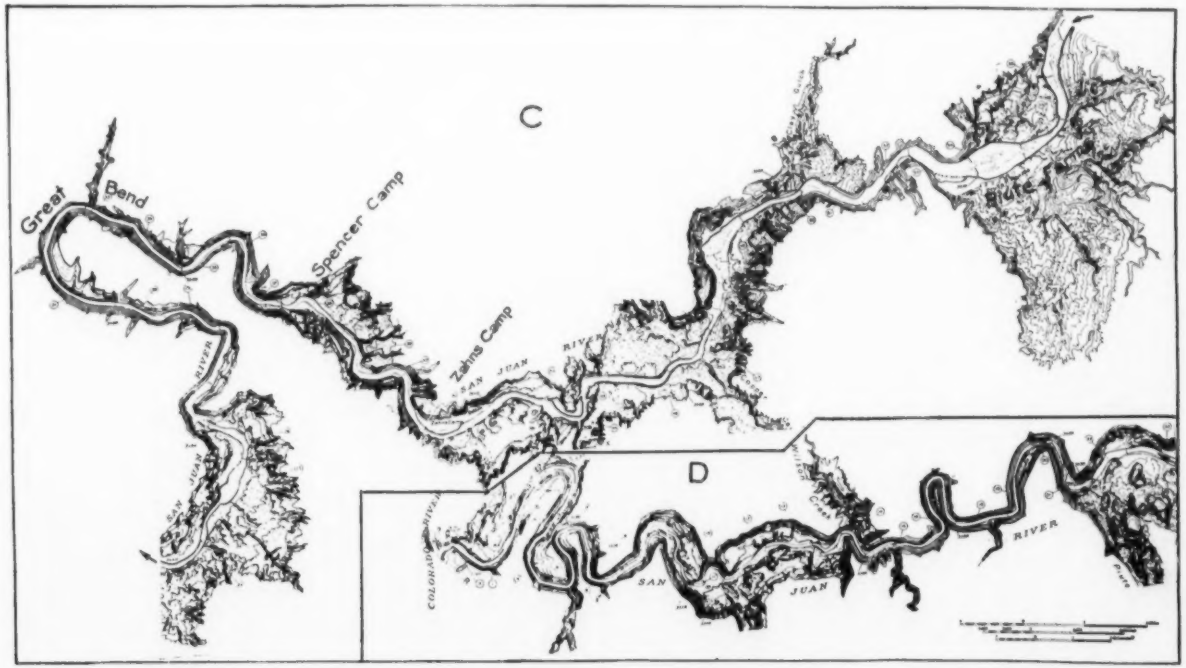

FIG. 2.—Map of San Juan River, Utah. (*C*) Clay Hill Crossing to point below Great Bend; (*D*) from below Great Bend to Colorado River. Contours below 3,900 feet, *United States Geological Survey*.

cussion are much less strongly developed than in the section near Goodridge.[1]

The Great Bend.—A striking feature on the lower San Juan River is the so-called Great Bend. This marked irregularity in the stream's course is evidently more than a meander, using the term in the ordinary sense, and some special conditions must have been involved in its origin. For several miles both above and below the Great Bend the present San Juan flows across weak formations (Chinle and Moenkopi), but in the bend proper the canyon is cut in relatively hard sandstone (Wingate, Todilto, Navajo), the underlying soft strata not yet having been reached by erosion. This distribution of formations in the canyon is consequent upon the local geologic structure, the strata being inclined to the west and northwest at an angle of two to five degrees from the Balance Rock anticline which crosses the river near Zahns Camp to the Wilson syncline which lies between the San Juan and the Colorado. A normal course consequent on the rock structure is very obviously a down-dip westward continuation of the course of the river above the bend so as to intersect the Colorado near the mouth of Escalante River. Instead of following this course the river turns 180 degrees and, after flowing for some miles in a direction exactly opposite to the direction of dip, turns irregularly southward and westward and crosses approximately at right angles a rather prominent anticline and syncline before reaching the Colorado.

Patently, this course is entirely independent of the rock structure. These structural features are in all probability of the same geologic age as the folds in adjoining territory which affect Cretaceous rocks but which do not involve the Eocene Tertiary. If this is the case, the development of the rock structures must long antedate the appearance of San Juan River, and the lack of adjustment of the river to the geologic structure must be assigned either to superposition from a widespread Tertiary cover which has subsequently been stripped away from this entire region or to peneplaination which

[1] H. D. Miser submits the following note: "Near the Clay Hill Crossing and Piute farms there has been a westward (monoclinal) shifting of the San Juan River channel down the dip slope of the hard Coconino sandstone. This is indicated by a great stairway of numerous extensive gravel-floored terraces on the east side of the river. The terraces range in elevation from less than 20 feet to 500 or 600 feet above the San Juan."

permitted the ancient San Juan to wander over hard and soft rocks without reference to geologic structure. Structural relations indicate that the river's course is not assignable to a former peneplain stage in which the smoothly worn rocks were unable to control the placement of the river, for the position of the river must earlier have become established, if influenced at all by rock structure, in a very different course, and there is no adequate explanation under this hypothesis for the development of the present drainage. These considerations apply to the vicinity of the Great Bend quite as much as to other more pronounced structural anomalies.

The character of the rock walls in the Great Bend indicates that corrasion has been mainly downward,[1] the inner convex wall of the bend being little, if any, less steep than the concave outer wall. The pattern must therefore have been developed before intrenchment into the massive, hard sanstones. Applying to this portion of the river the tentative conclusions reached in connection with the intrenched meanders of the Goodridge section, it may be observed that if the river at one time meandered along this section of the canyon at an elevation above the present, which is comparable to that assumed upstream, this earlier stream would have been flowing in the soft, easily eroded shales of the Cretaceous. Underlain by the resistant Dakota and McElmo grits, and influenced by a strong northwestward dip, it seems entirely expectable that a certain amount of adjustment to differences in rock hardness should take place by lateral shifting in the zone of weak sediments. The effect of this shifting was, presumably, to elongate greatly the northwestward swing of the river, and accordingly there appears a very plausible reason for the development of this peculiar feature. While erosion in the soft Cretaceous shales was doubtless relatively easy, the development of a direct pathway into the Colorado, only a short distance to the northwest, appears probably to have been prevented by an escarpment of massive Cretaceous sandstones in the Wilson syncline west and north of the river. This sandstone now outcrops

[1] H. D. Miser notes: "There was a very little shifting, as shown by the character of the walls and the occurrence of gravel benches, one being 3½ miles below Spencer Camp at an elevation of 400 feet above the river. Other benches inside the bend stand 270 feet above the river."

a short distance north of Colorado River and normally overlies the shale, so that the conditions here outlined doubtless obtained along San Juan River at one time. The Great Bend, therefore, appears to represent a partial adjustment to rock structure and hardness in the latter part of an erosion cycle which preceded the present period of deep canyon-cutting. When uplift affected the drainage of the region and the San Juan began actively to corrade its channel, this portion of the river's course was let down at once into resistant sandstone rocks, and underlying soft strata here have not yet been reached in the main part of the bend.

Below the Great Bend.—On the lower San Juan, between the Great Bend and the Colorado, there are well-defined meander loops which in some places are almost completely closed (Fig. 2). Excepting the lowermost few miles, all of this section of the canyon has been deepened sufficiently to expose the soft Chinle shale which underlies the massive sandstones that compose the upper canyon walls. Where the Navajo Mountain anticline crosses the river the sandstone cliffs have receded approximately a mile from the river, but elsewhere they follow very closely each of the irregularities in the stream course, and the steepness of the points of spurs in the meander bends indicates that erosion has here also been almost entirely vertical. Even where three or four hundred feet of the Chinle are exposed, there has been inappreciable shifting of the river, and the present pattern accordingly represents closely the meandering course of a stage antecedent to the intrenchment. Projecting the assumed profile indicated by conditions in the Goodridge and Great Bend sections of the river, it appears that all of the intrenchment in this section, except the final phase in which the bordering sandstone still serves effectively to guard the position of the river, has faithfully retained the outlines of the earlier stream (Fig. 3).

Summary.—The conditions which are observed along the San Juan seem clearly to indicate that most of the meanders have been inherited from an earlier mature, or perhaps even a moderately old, valley, on the flood plain of which the former San Juan meandered after the normal fashion of a stream at this stage. The relative position of this inferred ancestral stream, based on this study of the inclosed meanders, must have been approximately 1,100 feet above

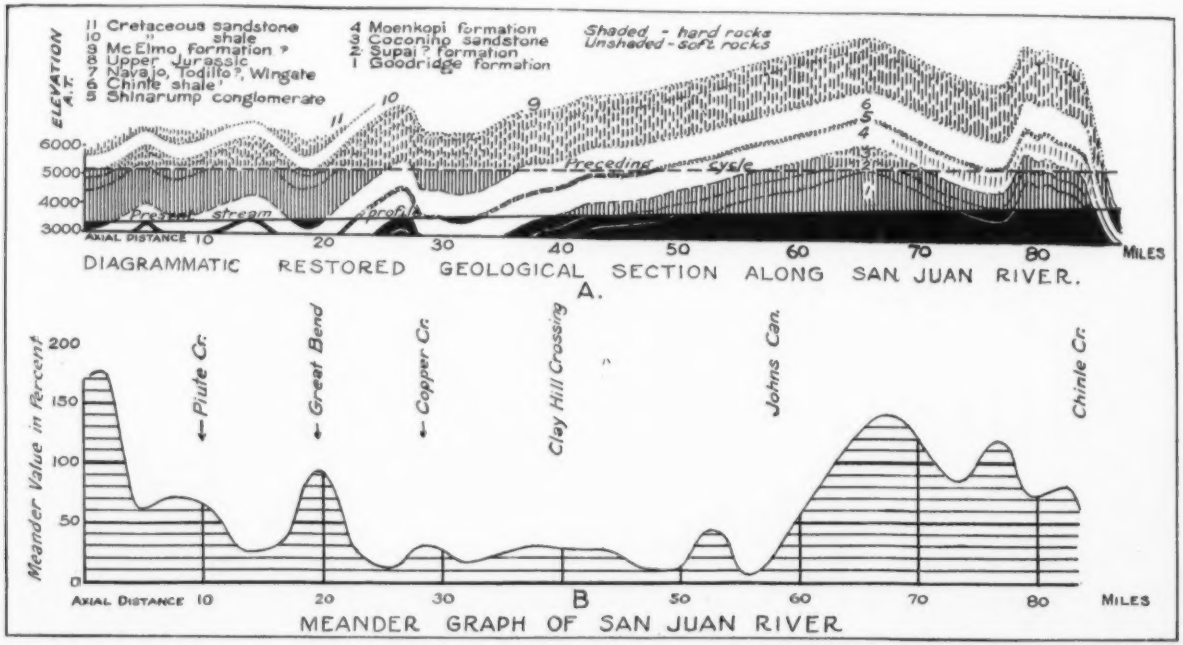

FIG. 3.—(*A*) Restored geological section along San Juan River showing inferred position of river profile in preceding erosion cycle. (*B*) Meander graph of San Juan River.

the present stream at the head of the canyon near the mouth of Chinle Creek, and around 1,800 feet above the mouth of the San Juan. The present elevation of the obliterated old plain would be, accordingly, about 5,300 feet at the head of the canyon, and around 5,000 to 5,100 feet at the mouth of the river.[1] The earlier graded stream, presumably, of course, had a much less steep gradient than at present, but whether the uplift that rejuvenated erosion was broadly uniform in amount or was accompanied by some warping is uncertain. Evidence seems to support the conclusion that warping was unimportant. Where the bed of this former stream was underlain by hard rocks the meandering pattern has been more or less faithfully preserved, as in the vicinity of Goodridge and near the mouth of the river. Where for several hundred feet the bed of the stream was let down on weak strata, the meander pattern appears to have been obscured or entirely changed.

Although in the nature of the case actual remnants of this inferred peneplain in the vicinity of the river have probably disappeared on account of active corrasion in the present cycle of canyon-cutting, or, if present, are not reliably identifiable, it is suggested that the described features in connection with the development and distribution of the meanders along the stream furnish a basis for conclusions concerning at least the approximate elevation

[1] The following note, kindly submitted by Mr. H. D. Miser after reading the manuscript of this paper, is of special interest in view of the close accordance of inferences reached by the writer from study of stream meanders with observations of local-erosion surface remnants, not previously known to him: "Monticello, 7,037 feet above sea-level, is located on the gentle eastward-sloping remnant of a peneplain which dips eastward from the Abajo (Blue) Mountains. The peneplain is apparently continuous from the Blue to the LaSal Mountains, and extends many miles to the east. The snow-covered mountains and mesas of Colorado such as the La Plata, Piute, and Mesa Verde, apparently lie above its level. At and near Monticello the peneplain is capped by a few feet of water-worn cobbles and pebbles and surficial loam. The underlying rock at Monticello is the Mancos shale. The peneplain is about 200 feet higher at a point five miles south of the town.

"From the vicinity of Monticello the peneplain extends southward past Blanding to a point 14 miles south of Blanding. It also has a gradual slope in this direction, and on its southern edge has an elevation of 5,211 feet above sea-level. The Dakota sandstone, the Mancos shale, and surficial beds of gravel and loam underlie the peneplain at all places in this stretch, just as they do near Monticello. The San Juan Canyon, whose head at the mouth of Chinle Creek has an elevation of 4,200 feet, has been cut below the level of the peneplain."

of this peneplain stage. On a restored geological section drawn along the river's course, an empirical up-and-down shifting of a profile for the antecedent San Juan calls attention to the fact that in only one position does this assumed stream-level afford satisfactory basis for the interpretation of the distribution of meanders along the river. The position of the line thus drawn (Fig. 3) coincides closely with field evidence concerning the probable elevation of the older river and the amount of intrenchment which has subsequently taken place.

INCLOSED MEANDERS OF GREEN RIVER

All of Green River below the town of Greenriver, Utah, presents a rather exceptional example of an inclosed meandering stream.

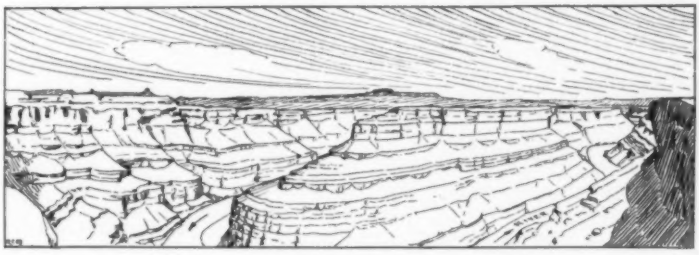

FIG. 4.—Intrenched meander on Green River, 1 mile above its mouth. Canyon walls composed of Goodridge, Supai (?), and Coconino (?) formations; outliers of Wingate sandstone on skyline in distance.

The general pattern of the meanders resembles that of Colorado River above Cataract Canyon. To the north, the inclosing walls are very low, for the river is bordered by relatively weak rocks belonging to the Cretaceous and to parts of the Upper Jurassic. The meanders of Green River belong apparently to the intrenched type, having been developed at an earlier stage in river history and incised in the hard rocks of the region on account of uplift and consequent rejuvenation of stream erosion. A sketch of a part of the intrenched meandering valley where the river is carved in the hard limestones and sandstones of the Permian and Pennsylvanian is shown in Figure 4. The ends of the projecting spur are not different in topographic form from the opposite walls on the outer side of the me-

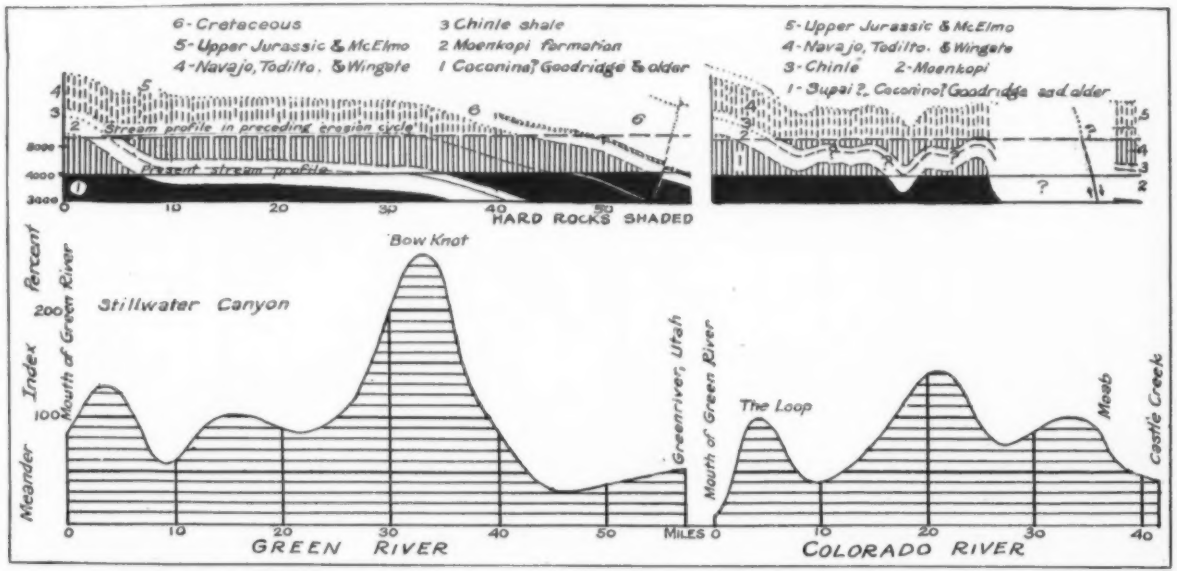

FIG. 5.—Restored geological sections along Colorado River from the mouth of the Green River to Castle Creek, Utah, and of Green River below the town of Greenriver; showing position of inferred river profiles in preceding erosion cycle. Meander graphs.

ander bends. The zone of slopes and weak cliffs in the upper middle part of the canyon sides is due to less resistant strata, possibly equivalent to the Supai formation.

In the part of the river's course between the Bow Knot and the point where the Paleozoic rocks appear, a few miles above the Colorado, the Green is now cutting in weak strata (Chinle and Moenkopi) (Fig. 5). The valley is being widened, consequently, both on account of horizontal cutting by the river and by wasting of the soft rocks which causes the retreat of the overlying sandstone cliffs by sapping. In places where meander bends are encroaching upon a narrow intervening divide, cut-offs are imminent in the near

FIG. 6.—The Bow Knot on Green River, 51 miles below Greenriver, Utah. Palisade-like cliffs composed of Wingate sandstone capped by Todilto; Chinle exposed in slopes. Lateral corrasion is narrowing the neck between the two meander bends.

geologic future. Flood-plain scrolls on the inner and upstream sides of bends indicate that the river is essentially at grade in this section. Obviously, however, as the lower parts of the Colorado system are brought nearer to sea-level there will be an accompanying deepening of the valley of the Green. Figure 6 shows the canyon of Green River at the Bow Knot, where palisade cliffs composed of Wingate sandstone, capped by Todilto thin-bedded sandstone, overlie the softer Chinle formation. A view of the canyon at a point some 25 miles downstream (Fig. 7) shows the greater thickness of soft formations which is here exposed and the evident shifting in the present meanders.

INCLOSED MEANDERS ON COLORADO RIVER

Colorado River from Moab, Utah, to Lees Ferry, Arizona, has, in many places, a distinctly meandering course. It is almost continuous-

ly, and somewhat narrowly, inclosed by canyon walls, which in most places rise several hundred feet above the river.

Castle Creek to Cataract Canyon.—The meander pattern of Colorado River above the mouth of the Green resembles that of Green River, rather than the Colorado below the confluence of these two streams. This is due to the prevalence here of what may be termed secondary meanders, irregular twists and bends which in places seem to be superposed on a major meander series. Information concerning the geology of this portion of Colorado River is somewhat less definite and reliable than for other portions. For a

FIG. 7.—A portion of the Green River valley 25 miles below the Bow Knot. Wingate sandstone forms the upper cliffs, Chinle and Moenkopi the underlying slopes; a prominent bench at intermediate levels is formed by the Shinarump conglomerate. The river is cutting sideward in the zone of softer rocks.

considerable distance upstream from the mouth of the Green it is known that Permo-Carboniferous sandstones and limestones compose the lowermost parts of the canyon walls, and that a few miles below Moab there are several rather prominent anticlines and synclines which are traversed by the Colorado.[1] At Moab the Colorado crosses a prominent northwest-southeast–trending fault with downthrow on the northeast, which in places displaces the rock strata more than 3,500 feet, and there is probably some block-faulting in the Moab Valley. A few miles above Moab the base of the Wingate sandstone is only a few hundred feet above the river, and the thin Chinle shale is seen resting with marked angular unconformity on

[1] H. W. C. Promell, "Geology and Structure of Portions of Grand and San Juan Counties, Utah," *Bull. Amer. Assoc. Pet. Geol.*, Vol. VII (1923), pp. 384–99.

the underlying Moenkopi.[1] This region has been involved in more or less important structural displacements incident to the formation of the Abajo and LaSal mountains, and there are noteworthy changes in the character of some of the formations on account of proximity to the old Uncompahgre land-mass on the east. While the Wingate and Navajo are very similar lithologically to typical exposures of these formations in the region far to the southwest, the relation of the Triassic and Permo-Carboniferous to the Cataract Canyon and San Juan sections is not so clear. It is reported that the Moenkopi ranges in thickness from over 1,200 feet to less than 200 feet in very short distances horizontally.[2]

Near the mouth of Green River and at The Loop, the canyon walls are approximately 1,000 feet high. They are formed chiefly by hard rocks belonging to the Goodridge and the Supai (?). Relatively thin capping sandstones may represent the Coconino (?), which is so extensively developed in Cataract Canyon, but the soft rocks above the canyon rim are here stripped back for some miles from the river (Fig. 4). The spurs projecting into meander bends are practically counterparts of the walls along the concave outer sides of the bend, and there is no evidence at all of the development of slip-off slopes. Accordingly, there seems to be no reasonable doubt that the meander patterns of this section had been developed before the incision into rocks which form the present canyon walls had been commenced. Before intrenchment the Colorado must have been at least 1,000 to 1,200 feet above its present level in this section. Near the mouth of Castle Creek, a few miles above Moab, the canyon walls are about 1,100 feet high, and there is a complete absence of slip-off slopes on the spurs in meander bends. Todilto and Wingate sandstones rim the canyon in this section.

The occurrence of typical intrenched meanders of considerable depth, above Moab and near the mouth of the Green, indicates that the meanders in these stretches were developed before the river began to cut its present canyon. In the space between Moab and The Loop, the river must have been let down through the zone of

[1] Whitman Cross, "Stratigraphic Results of a Reconnaisance in Western Colorado and Eastern Utah," *Jour. Geol.*, Vol. XV (1907), p. 695.

[2] H. W. C. Promell, *op. cit.*, p. 391.

soft formations represented by the Chinle and Moenkopi (Fig. 5). Owing either to the relative thinness of these softer formations, or perhaps on account of the greater thickness of the Shinarump, which is reported to have a thickness of 200 feet in the Moab district,[1] intrenchment through the zone of these soft rocks seems to have been ineffective in modifying very importantly the probable original meander-pattern. The subordinate meanderings in this section which have been described may, however, be due to horizontal shifting in this zone of weak strata. If, as seems probable, the hard rocks of the Cataract Canyon section of Colorado River had been reached in the downcutting of the river during the latter part of the erosion cycle in which the described meanders of the upstream section were formed, the barrier composed of these hard rocks may have been largely responsible for the gradation of the valley of the Colorado above Cataract Canyon and on Green River, and to have aided in the development of the greater meandering here.

Cataract Canyon.—In Cataract Canyon the rock walls rise very steeply above the river and follow the stream closely. According to available maps[2] the elevation of the rim of the canyon is about 5,000 feet, which, with information concerning the stream profile obtained in recent river-surveys, indicates a height of about 1,100 feet to 1,500 feet for the canyon walls. The rock formations which compose these walls consist mainly of hard limestones and sandstones (Goodridge, Supai, and Coconino ?) for which Paige[3] reports a total thickness of approximately 2,500 feet (Fig. 8). The Colorado has a slightly irregular course in Cataract Canyon, and these irregularities have evidently been inherited from a stage in the river's development when intrenchment of the canyon had not yet started. The rocks are the same as those in the upper San Juan Canyon, where rather intricate, deeply intrenched meanders occur, and accordingly, similar intrenched meanders should be found in Cataract

[1] H. W. C. Promell, *op. cit.*, p. 391.

[2] "LaSal and Henry Mountain Quadrangles," *U.S. Geol. Survey.*

[3] Sidney Paige, in C. R. Longwell and others, "Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona," *U. S. Geol. Survey, Prof. Paper 132* (1925), p. 8.

Canyon, unless Colorado River did not have a meandering course in this section at the time of uplift of the region. If the relative lack of development of meanders is associated with active downward corrasion through the zone of soft rocks which overlie the Coconino (?) sandstone, an amount of downward corrasion which is much greater than represented in the present height of the canyon walls must be predicated (Fig. 9). On the other hand, the observed slight irregularities in the river's course in Cataract Canyon might be anticipated if the hard rocks had been reached in the latter part of the erosion cycle preceding the present, and if insufficient time had

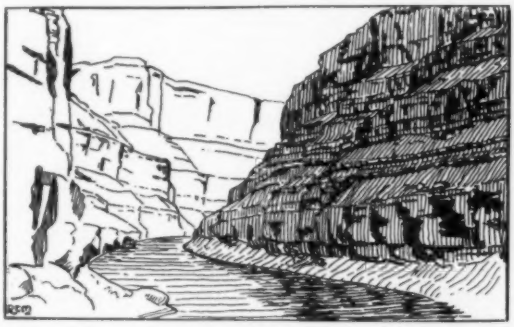

FIG. 8.—The interior of a portion of Cataract Canyon. Walls composed of Goodridge, Supai (?), and Coconino (?) formations.

elapsed before uplift to permit widening and thorough grading of the valley. This suggestion affords a basis for explaining the rather complex meanders above Cataract Canyon and relative absence of meanders in the canyon, where otherwise they should be well developed, and it permits satisfactory correlation with inferred pre-canyon cycle erosion-levels elsewhere.

Glen Canyon.—Throughout Glen Canyon, which extends from near the mouth of the Fremont to Lees Ferry, Colorado River has numerous but not complex meanders (Fig. 10). Between the mouth of the Fremont and a few miles below Hite the lower part of the canyon consists of weak rocks which underlie the Wingate sandstone, and the valley is, correspondingly, somewhat wide. Except for a short space where Waterpocket fold crosses the Colorado a few miles

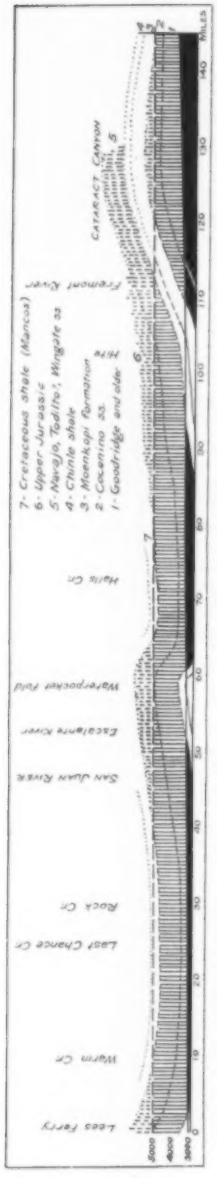

FIG. 9.—Restored geological section along Colorado River from the mouth of Green River to Lees Ferry, showing position of inferred river profile in preceding erosion cycle.

above Escalante River, all of Glen Canyon is carved in massive sandstones (Wingate, Todilto, and Navajo). These sandstones rise very steeply, even vertically, from the water's edge, and they reach a height of several hundred, or in places more than a thousand, feet above the river. Owing to the geological structure of the region, these sandstones are relatively low between Warm and Rock creeks and in the vicinity of Halls Creek (Fig. 9), and the inner walls of Glen Canyon are here lowest, but at only a short distance from the inner cliff, rise walls composed of the higher Jurassic sandstones. Many of the meanders of Glen Canyon show no appreciable evidence of lateral corrasion or sweep during downward intrenchment, but others show more or less definite evidences of horizontal shifting in the position of the river's course.[1] In a number of places there are very definite slip-off slopes covered by patches of river gravel, and these, in connection with the markedly undercut cliffs of the outer and downstream sides of the meander bends, show the operation of effective lateral cutting. In general, however, this horizontal shifting appears rather to change slightly the outline of the meander bends and to move them downstream than to suggest the development of the meanders from original slight irregularities in the river's course.

That the Colorado was meandering considerably before the intrenchment

[1] Raymond C. Moore, *op. cit.*, Fig. 6, p. 41.

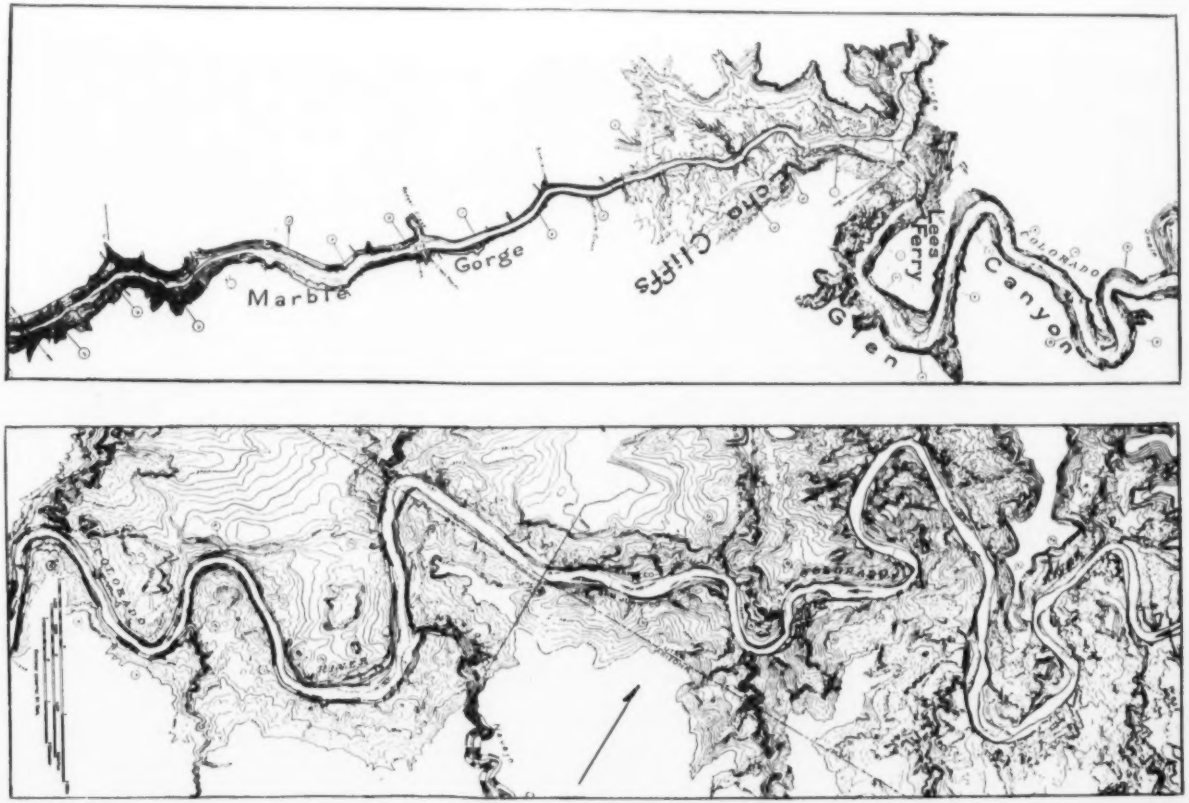

FIG. 10.—Map of parts of lower Glen Canyon showing typical inclosed meanders, and the upper end of Marble Gorge with nearly straight course. Contours below 3,900 feet and 3,100 feet, *United States Geological Survey*.

which formed the present Glen Canyon took place appears certain. The height of the canyon walls, which affords a minimum measure of the amount of intrenchment, is in several places more than 1,000 feet, and near Lees Ferry it is nearly 2,000 feet. The elevation of the sandstone plateau in the vicinity of Lees Ferry, and projected gradients along Colorado River and tributary streams where data from meanders and erosion remnants afford clues, suggests that the pre-canyon-cycle Colorado had a position approximately 1,900 feet above the present river-level at Lees Ferry, that is, an elevation of about 5,000 feet. If this is correct, there were nearby plateaus that rose 1,000 to 2,000 feet above the Colorado at that time. Paria Plateau, whose bordering cliffs are less than two miles from the river near Lees Ferry, rises to 6,000 feet at this place, and farther southwest, where the cliffs are about five miles from the river, to more than 7,000 feet. The south end of Kaiparowits Plateau, opposite Navajo Mountain, less than 5 miles from the river, is over 7,250 feet above sea-level. If the essential features of the present meander-pattern of the Colorado were developed as the normal expression of a graded condition on a former flood-plain, it appears that practically all of the downward corrasion incident to recent uplift must have been through hard rocks which were competent to preserve fairly faithfully the geographic plan of the earlier Colorado (Fig. 9).

The relations of the inclosed meanders in Glen Canyon to the Echo Cliffs monocline at Lees Ferry, where the meanders suddenly disappear, are such as to suggest a causal relation between them. Hard rocks (Kaibab limestone) are exposed in the river bed just below the Ferry, and there is a marked change in the gradient of the Colorado, from a gentle slope of about 2 feet per mile above this point to about 10 feet per mile below. Upstream there are almost no rapids until one reaches Cataract Canyon; downstream, rapids are very numerous. Gregory[1] emphasizes the importance of the hard-rock barrier which is reached at Lees Ferry, but he does not discuss the inclosed meanders that characterize Glen Canyon, nor

[1] H. E. Gregory, "Geology of the Navajo Country," *U.S. Geol. Survey Professional Paper 93*, p. 126.

the contrasting straightness of Marble Canyon. Jefferson,[1] however, attributes the development of meanders in Glen Canyon to the establishment of a local, temporary base level by the hard rock obstacle at Lees Ferry, apparently forgetting that the meanders are deeply intrenched, and that at a stage before intrenchment there was no hard rock obstacle at Lees Ferry.

Marble Gorge.—With the possible exception of the symmetrically rounded bends to right and left at a distance of 40 to 45 miles below Lees Ferry, Marble Gorge, and practically all of Grand Canyon, offers nothing that can well be designated a meander (Fig. 10). Since meanders are normally developed in the gently graded middle and lower reaches of a stream course, we may ask whether their essential absence from the Colorado River Canyon below Lees Ferry is due to some condition which caused them never to develop, or whether, having at one time been formed, they have subsequently disappeared.

At the present time all of the softer rocks which underlie the Kaibab limestone have been swept off for a distance extending many miles back from the river. The dip-slope formed by the top of the Kaibab rises gently southwestward, from an elevation of about 3,100 feet near Lees Ferry to about 5,500 feet on Colorado River 40 miles below the Ferry. Southwestward, in the Grand Canyon district, it rises in many places to more than 7,000 feet, and on the Kaibab Plateau its elevation is more than 9,000 feet. The course of Colorado River with reference to rock structure, in the light of other evidence, admits no question but that at one time the river flowed in a position many hundreds of feet higher with reference to the rocks than now. In proportion to the amount of this difference in elevation, a considerable part of the river's course below Lees Ferry must then have been on the soft rocks of the Moenkopi and Chinle formations, and the cutting away of these soft rocks led progressively to the intrenchment of the stream in the underlying Kaibab (Fig. 11). If, as seems to be indicated clearly by the inclosed meanders just east of Lees Ferry, this former stage of the Colorado

[1] Mark S. Jefferson, "The Antecedent Colorado," *Science*, new series, Vol. VI (1897), pp. 293–95.

was elevated above the present position of the stream by at least the measure of the intrenchment which has occurred above Lees Ferry, the complete thickness of the Moenkopi and Chinle must have been below the former river-level, at a point several miles below Lees Ferry, and these soft rocks, diminishing progressively in thickness, would have extended some forty to fifty miles southwestward.

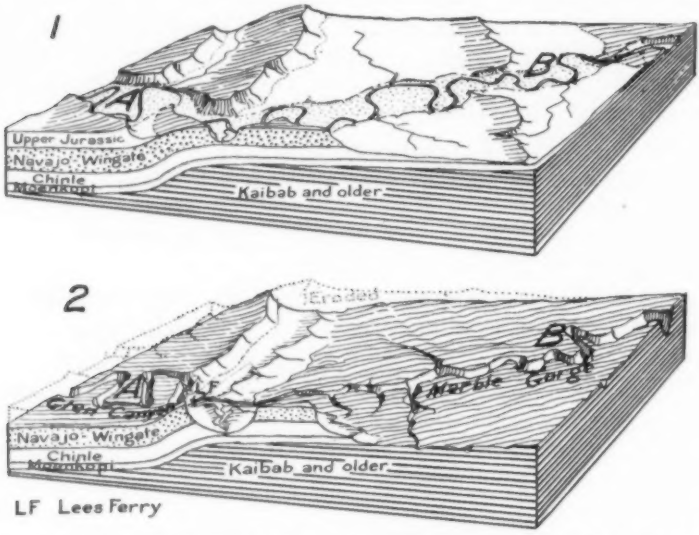

FIG. 11.—Block diagrams showing (1) probable physiographic conditions in the vicinity of Lees Ferry during latter part of inferred earlier cycle of erosion and (2) present conditions. Following uplift, meanders at *A* were intrenched in Navajo sandstone and those at *B* in Kaibab and older rocks. The soft rocks (Chinle-Moenkopi) have been stripped back to the position of the Echo Cliffs monocline at Lees Ferry (*LF*) and the course of the river between *LF* and *B* has been markedly straightened if meanders were once present here.

It is probable that the adjustment of the Colorado gradient to the soft rocks would have occasioned the development of meanders, and these should have extended not only through the section above Lees Ferry, but also downstream some thirty or forty miles to the point where, at the time when the meanders were formed, the bottom of the soft rocks covering the hard formations was reached (Fig. 11, *a*)

Following uplift in the Grand Canyon and plateau districts, which permitted the Colorado to corrade its bed actively, the section of the stream flowing on weak rocks between the present middle portion of Marble Gorge and Lees Ferry should have been subjected to a gradual modification in form, resulting at length in the effacement of meanders. Certainly meanders are now lacking along this part of the Colorado. However, at about the point where this older stream-bed had presumably already reached the hard formations that underlie the Moenkopi, there are two or three not untypical meander bends (Fig. 11,*b*). As has been observed, in the upper parts of Colorado River, where there are many deeply intrenched meanders, it might be expected that these features would persist in the hard rocks which extend almost continuously beneath the Kaibab.

The absence of intrenched meanders in the lower part of Marble Gorge and throughout the Grand Canyon seems at first to be at variance with what might be expected if the general conditions described on the upper part of the Colorado are rightly interpreted. Except for two weak formations which are not more than 500 feet in individual thickness, and excepting portions of the Algonkian which appear in a few places in the bottom portion of the canyon, all of the rocks are hard and should preserve essentially the earlier plan of the river in this section. Because the hard rocks alternating with the soft formations which have been mentioned are entirely competent to prevent significant lateral shifting, it can only be assumed that the course of Colorado River before the recent intrenchment was not essentially different from the present course. This, it appears, may be explained plausibly by calling to mind that if the Colorado had established a grade at the approximate position which has been indicated, the portion of the valley which is included in the lower Marble Gorge and in the Grand Canyon would already have been cut from a few hundred to more than 2,000 feet in the resistant formations which now form the rim of the bordering plateaus. Even though considerable physiographic maturity had been attained in other parts of the stream course, and even though this beginning of the Grand Canyon had been appreciably widened, it is possible, or indeed probable, that no broad flood-plain with meandering stream would have been developed in its bottom. Accordingly, on

renewed uplift, there should be little indication in the pattern of the stream of this early canyon stage, and because of very active erosion within the canyon, there might be no reliably identifiable traces of the old valley. Perhaps, however, it is significant that the noteworthy change from the very narrow Marble Gorge type of canyon to the much wider, intricately dissected, Kaibab type takes place a short distance downstream from the point where the ancient Colorado is inferred to have entered the hard rocks at the close of the erosion cycle preceding the present. Supposed evidences of an older erosion cycle in the form of a wide upper-valley cross-section and more or less prominent benches at certain elevations appear, without exception, so far as known to the writer, to be of structural origin. In the nature of the case, it seems that such evidences are more likely to be lost than to be preserved.

Gregory[1] compares the Glen Canyon and Marble Gorge sections of the Colorado River Valley and concludes from their general similarity in width, and because they form an essentially continuous trench, that they are of approximately equal age. He calls attention, however, to the very great difference in the amount of erosion which has been accomplished in the region bordering these two canyon sections, practically all of the rock strata down to the top of the Kaibab having been removed west of the Echo Cliffs monocline, while to the east and north there is still present all of the Triassic, most of the Jurassic, and much of the Cretaceous, sections. These broad inequalities in the degradation of the region seem undoubtedly assignable to an earlier cycle of erosion than the present, but, as previously suggested by the writer, an undetermined part of the greater erosion in the Grand Canyon district may have taken place before Eocene deposition in this region.

In contrasting the Glen Canyon and Marble Gorge sections of Colorado River, Gregory points out that the Echo Cliff monocline has been a very important obstacle in the path of the river, the resistant rocks which are here brought to the surface serving so to impede the downcutting of the river that in Glen Canyon the profile of the river is very gently graded. Not only is there an almost complete absence of rapids in Glen Canyon, but in places there are

[1] H. E. Gregory, *loc. cit.*

narrow flood-plain scrolls. There is a similar contrast between Cataract Canyon and the valleys of Green River and the Colorado above. These sections of steep and gentle gradients seem obviously controlled by the differences in the hardness of the rocks in the portions of the canyon now being eroded by the river. The hard rocks do constitute an obstacle which operates to control erosion in the river above them, but the local base level which they tend to form is constantly being lowered. If the occurrence of hard rocks in the path of the Colorado in an earlier erosion cycle served to produce long, graded sections of the river valley where it crossed weaker rocks, and to develop flood-plain meanders, such hard-rock barriers seem not to have been associated in more than a general way with the present distribution of hard rocks in the canyon bottom. As has been pointed out, the end of the graded section in what is now Glen Canyon must have been formerly many miles below the place where the Echo Cliffs moncoline crosses the river. The restriction of the inclosed meanders to the canyon east of Lees Ferry is evidently not due to the present appearance of the hard Kaibab limestone just below the Ferry, but to the combination of structural, stratigraphic, and physiographic conditions, which has brought about an obliteration of meanders, probably once continuous, downstream from those intrenched in lower Glen Canyon.

INCLOSED MEANDERS OF MINOR STREAMS

As described in the writer's paper on the origin of inclosed meanders on Colorado Plateau streams, those of the smaller tributaries of the Colorado are chiefly of the "ingrown" type, and may be explained by conditions of erosion during the present cycle. Therefore they do not represent inheritance of meanders from an earlier erosion cycle.

Some of the streams, like the Fremont, Escalante, and Paria, clearly antedate the present physiographic cycle. This is shown rather by their independence of rock structure than by characteristics of their canyons, although the inclosed meanders of the two larger, first-named streams appear to be much-modified inherited meanders. The writer has not had opportunity to study carefully the valley of the Fremont, though he has observed part of its head

waters where, without regard to structure, valleys are cut across upturned strata of San Rafael swell and Waterpocket fold.

Escalante River, similarly, cuts across anticlinal and synclinal folds, but in its lower part follows a course which is roughly parallel to the strike of the rocks. It is, however, perched in a seemingly anomalous position midway down a long sandstone slope on the west side of Waterpocket fold. In front of the Straight Cliffs of Kaiparowits Plateau, which parallel the river a few miles to the southwest, a soft-rock depression unoccupied by a stream is much lower than the rim of the Escalante Canyon. The course of the Escalante seems to have been established in an earlier erosion cycle in the soft-rock valley which is now shifted down the dip, while, as a result of uplift that caused canyon-cutting, the river carved its pathway where it chanced to be when rejuvenation occurred. If this is true, the elevation of the present canyon rim should have relation to that of the old erosion-level on the Colorado, estimated at about 5,100 feet at the mouth of the Escalante. Examination of the topographic map (Escalante quadrangle), which is not a very good one, bears out this supposition. These observations are, in part, basis for inference that the meanders of this stream are greatly modified inherited meanders.

Paria River, and even several of its minor tributaries, exhibit a surprising lack of adjustment to rock structure, but inclosed meanders observed here do not aid very much in the attempt to decipher physiographic history.

RELATION OF INCLOSED MEANDERS TO PENEPLAIN REMNANTS

Remnants of peneplains have been observed in different parts of the plateau country, but in almost all cases these occur only at considerable distances from the axial portions of the drainage. Dutton[1] first called attention to evidences, in several parts of the plateau country, of eroded surfaces which indicate a former extensive cycle of erosion, and he concluded that, prior to the carving of the present Grand Canyon, the region adjacent to Colorado River was

[1] C. E. Dutton, "Tertiary History of the Grand-Canyon District," *U.S. Geol. Survey Mon. 2*, 1882.

broadly flat and lacking in any deep valleys. Robinson[1] has described similar evidences in a wide territory embraced in the Colorado drainage basin, and has presented a detailed outline of the physiographic history of the region, based on interpretation of the features reported. More recently, a summary of peneplain evidences in the Navajo country, south of San Juan and Colorado rivers, has been published by Gregory.[2] These peneplain remnants range in elevation from about 4,000 to 7,000 feet. Some of them are doubtless of small extent and are controlled by local geologic features. The higher remnants seem very possibly to accord with the inferred graded stage of the main drainage when the meanders which are now deeply intrenched were developed; the lower ones probably mark a temporary halt in the degradation of the areas where they occur. The outline of probable physiographic history which is offered by Gregory[3] coincides essentially with the conclusions reached by the writer from the present study of evidences, which have not been considered in such detail by earlier students of the plateau problem.

Clearly defined remnants of an old erosion surface were observed by the writer on the upper Paria Valley in the vicinity of Tropic and Cannonville, Utah. Here there are large surfaces gently inclined toward the river and at elevations from 300 to 500 feet above the adjacent recently carved stream valleys, these surfaces beveling rather evenly across hard and soft formations, and capped by an extensive cover of coarse water-worn gravel. The old graded plain occurs at an elevation of 6,000 to 7,000 feet, and its general relations to the topographic features of the Paria Valley suggest strongly that this surface is a part of the relatively gentle topography which had been developed throughout the plateau toward the close of the erosion cycle which has been called the Great Denudation. Apparently this cycle corresponds to the pre-canyon erosion stage, which is inferred in this paper from the character of the inclosed meanders

[1] H. H. Robinson, "The Tertiary Peneplain of the Plateau District and Adjacent Country in Arizona and New Mexico," *Amer. Jour. Sci.*, 4th ser., Vol. XXIV (1907), pp. 109–29.

[2] H. E. Gregory, *op. cit.*, pp. 120–23.

[3] *Ibid.*, p. 123.

of the Colorado and its main tributaries. It was interrupted by the uplift which inaugurated the present cycle of vigorous canyon-cutting. The streams have only partially dissected the peneplain remnants many miles back from the Colorado, and the present valleys have as yet cut only a small distance vertically into this old surface, but adjacent to the main drainage lines practically all traces of the former topography have disappeared.

At Cedar Ridge, east of the Echo Cliffs south of Lees Ferry, at an elevation above 6,000 feet, is a gently graded remnant of an older topography which is now being attacked by a tributary of the Colorado. The conditions here are well described by Davis,[1] who aptly remarks that this outlying district, like others, has apparently just received news of the great uplift which has caused the down-cutting of the main canyons, and belatedly is preparing to join the rest of the country in a descent to lower levels. This locality was also observed by the writer, who noted with much interest the features which are here clearly shown. Davis and others have described extensive peneplain remnants in the vicinity of Pipe Spring, the Wonsits Plateau, and places farther west.

The general elevation and geographic relation of these peneplain remnants accord very satisfactorily indeed with the general elevations of the former Colorado River drainage as interpreted on the basis of study of the inclosed meanders. This accordance seems to have significance, since the elevations on different streams were derived independently of one another and without any reference to peneplain remnants. Since actual peneplain remnants are, in the nature of the case, least likely to be preserved in proximity to the main river drainage, the clue which is apparently afforded by the evidence of the meanders is a significant one in reconstructing the physiographic history of the region.

It is not the writer's purpose to consider here the various physiographic evidences which are offered in the shallow upland valleys of the Grand Canyon district and adjoining high plateaus as described by Noble, Robinson, and others, nor to attempt to trace in detail the probable physiographic history of the plateau region. Attention rather is called to possible inferences which may be drawn from a

[1] W. M. Davis, *loc. cit.*

type of physiographic data that have in general been considered only in broadly qualitative, rather than quantitative, terms. It is believed that the distribution of intrenched meanders, in the light of information concerning the geologic conditions affecting their development, may be admitted as competent evidence in the interpretation of physiographic history. In a region such as the Colorado Plateau country, where the downward corrasion of streams is measured in such large amounts, and where denudation of the region as a whole is proceeding so actively, such evidences may be especially significant, for actual remains of surfaces produced in earlier erosion cycles are relatively evanescent, and when preserved may be difficult to recognize definitely.

CONCLUSIONS

1. The form of the canyons in several parts of the Colorado Plateau indicates clearly that at least one well-advanced cycle of erosion preceded the present. Meanders developed on flood plains in this preceding cycle have been preserved during the present cycle practically unchanged in some places, more or less modified in others.

2. The depth of the intrenched meanders apparently affords a minimum measure of the amount of downward erosion during the present cycle; but since identifiable peneplain remnants are commonly lacking in the immediate vicinity of the main drainage lines, it is not certain from this evidence that the total amount of downcutting during the present cycle may not exceed the depth of the canyons.

3. The absence of meanders on parts of streams that have deeply intrenched meanders in adjacent parts of their course appears to indicate, in some cases, that meanders once present have been lost; and in others, that meanders probably were not developed by the stream in such places during the previous erosion cycle.

4. Construction of geological sections along the streams, restoring eroded rocks, suggests that where hard formations immediately underlay streams at the time regional uplift brought the earlier erosion cycle to a close the courses of streams have been preserved with little change, but that where a considerable thickness of soft rocks has been encountered in downcutting the stream courses have

been greatly modified, in some cases with obliteration of meanders. An empirical adjustment of a hypothetical, gently sloping stream profile to the restored geological section, so that meanders at the assumed profile elevation will find hard rocks below them where intrenched meanders actually occur, and soft rocks where meanders are non-typical or absent, is commonly possible in only one position. This position presumably marks the stream profile before intrenchment in the present cycle. Independently determined on different streams, the profile elevations exhibit fairly close accordance, both with one another and with peneplain remnants that are known.

5. This study, if observations and reasoning are valid, indicates that the land surface at the close of the pre-canyon cycle was by no means flat. There were unreduced plateaus rising 2,000 feet or more within a few miles of the master-drainage, and at greater distances were higher plateaus and mountains, rising 5,000 to 6,000 feet above the main valleys. Unless there has been large, unrecognized differential warping subsequent to the close of the pre-canyon erosion cycle, the Colorado had already begun to carve the Grand Canyon before the present erosion cycle began. That this beginning of the Grand Canyon actually antedates the so-called "canyon cycle" is indicated by relations here described in Marble Gorge, and by the absence of intrenched meanders in the Grand Canyon.

THE ORIGIN OF THE COLOR OF RED BEDS[1]

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ABSTRACT

It is shown that the color of red beds is not due to a larger iron content, nor due to the mere presence of ferric oxide. It is the presence of red ferric hydrate and ferric anhydride which makes the rocks red. It is pointed out that conditions under which dehydration of ferric oxides can occur are to be investigated rather than conditions producing ferric oxide—these latter being the ordinary processes of erosion. The indisputable evidence that red beds are continental in origin explains why the red rocks retained their color, since the sediments were never exposed to the reducing action of the marine continental shelves.

In any discussion of red beds it may confidently be asserted at the start that the material causing the red color is iron. If the color were due to any unusual minerals, or combination of minerals, this would have long ago been discovered, and perhaps geologists would have had no red-bed problem. No unusual minerals are present characteristically in the red rocks, and since iron, in its various forms, is present in practically all rocks and is an adequate source of supply for the pigment of the red beds, there can be no question that the red beds owe their color to iron.

This being a fact, the following questions naturally arise: (1) Is the red color due to a larger iron content than that of the non-red rocks? (2) If not due to more iron, is it due to iron in a form different from that found in the non-red rocks? (3) If due to iron in a different form, what were the peculiar conditions of sedimentation which permitted the retention of such a form in the red rocks and not in the average sedimentary rocks?

If these three questions can be answered satisfactorily the red-bed problem, if there be one, will have been solved. The questions will be considered in order.

1. IS RED COLOR DUE TO LARGER IRON CONTENT THAN THAT OF NON-RED ROCKS?

The following figures were compiled by the writer for a discussion of the red sandstones and shales of the Newark system (Triassic) of the Eastern United States.

[1] Printed with the permission of the state geologist, Maryland Geological Survey.

Analyses of four red shales and one red sandstone from the Emmitsburg formation of the Maryland Newark, quoted by Mathews and Grasty,[1] give in percentage:

Fe_2O_3.....7.12; 5.61; 4.62, sandstone; 7.31; 6.15.

The average for the five is 6.16 per cent. These are typical dark-red shales. The authors say of these shales, "Though they contain from 5 to 7 per cent ferric oxide, nevertheless their content of iron is less than one would expect from their deep red color."

TABLE I

	1	2	3	4	5	6	7	8	9
	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent
Fe_2O_3	11.17	2.08	9.44	6.63	0.78	1.46	11.73	3.19	2.62
FeO	5.64	4.03	8.20	.....	.....	8.43	.....	4.87	5.63
	16.81	6.11	17.64	6.63	0.78	9.89	11.73	8.06	8.25

1. Andesite, Front Royal, Va.
2. Quartz porphyry.
3. Catoctin schist, Adams Co., Pa.
4. Harper's shale (Lower Cambrian), Washington Co., Md.
5. Shenandoah limestone (Cambro-Ordovician), Frederick Co., Md.
6. Diabase, Rocky Ridge, Md.
7. Slaty volcanics, Union Bridge, Md.
8. Sericitic schist, Frederick Co., Md.
9. Sericitic schist, Frederick Co., Md.

The sediments composing the Newark rocks must have been derived from adjacent rocks to the east and west. There is no reason for postulating great thicknesses of beds wholly different from the complex which now forms the Catoctin belt on the west, and the schists, argillites, and limestones of the Piedmont on the east. Indeed, this complex is so varied in composition it would be difficult to imagine a rock type which could have been present in large quantities in the past and not represented there now.

The analyses shown in Table I are of these adjacent rocks:

The average total iron content of these rocks, excepting the limestone, is 10.64 per cent.

It will be observed that except in the case of the thick Cambro-

[1] *Md. Geol. Surv.*, Vol. VIII (1909), p. 395.

Ordovician limestone the red beds of the Newark system in Maryland are actually lower in iron content than are the adjoining rocks —none of which are red.

Twelve analyses of non-red Martinsburg shale (Upper Ordovician), from Washington County, Maryland, give in percentage:

Total iron content—5.23; 8.11; 3.16; 2.61; 3.99; 2.34; 2.88: 4.82: 7.47; 4.97; 6.27; 4.27
Average total iron content—4.67

The Martinsburg shale is far from the present areas of the Newark, and probably contributed little to their formation.

That this relatively high iron content in the non-red rocks is not confined to the immediate vicinity of the Newark area the analyses in Table II show:

TABLE II

	1	2	3	4
	Per Cent	Per Cent	Per Cent	Per Cent
Fe_2O_3	.....	6.17	.....	6.37
FeO	14.87	.....	5.91	.....

1. Peach Bottom slates, near Delta, Pa.
2. Romney shale (Middle Devonian), Washington Co., Md.
3. Jennings shale (Upper Devonian), Washington Co., Md.
4. Conemaugh shale (Upper Pennsylvanian), Allegany Co., Md.

Three normal non-red shales from Ohio, Indiana, and Pennsylvania show in percentage:

Ohio	Indiana	Pennsylvania
4.32	7.59	6.07

That the Maryland red beds are not exceptionally poor in iron is shown by five analyses of New Jersey Newark rocks:

	Fe_2O_3 Per Cent
Brown sandstone from Whitehall	3.83
Brown sandstone from Wortendyke	3.00
Brown sandstone from Little Falls	1.34
Shaly brown sandstone, Belleville quarries	5.74
Drab sandstone from Plainfield	3.03
Average	3.39

Clarke[1] gives the following average iron content of seventy-eight shales and two hundred and fifty-three sandstones:

	78 Shales Per Cent	253 Sandstones Per Cent
Fe_2O_3	4.03	1.08
FeO	2.46	.30
	6.49	1.38

The average iron content of the Newark red beds in the New York–Virginia sheet ranges between 6.1 and 3.3 per cent, which gives an average of 4.7 per cent, or, approximately, 5 per cent of iron. The average of all adjoining rocks, except the limestone, is above this, about 6 or 7 per cent, and in exceptional instances, such as the green schists and phyllites, more than twice that of the red beds. These latter rocks are usually of a marked green color. Clearly, therefore, the answer to question 1 in the case of the Newark red beds at least is that the color is not due to a larger iron content than the non-red rocks.

2. IS COLOR DUE TO IRON IN FORM DIFFERENT FROM THAT FOUND IN NON-RED ROCKS?

The form in which iron is found as a pigment in rocks generally, where not as an ore or some other commercial deposit, is the oxide. As iron is an element of multiple valence it forms both ferrous and ferric oxides.

Ferrous oxide (FeO), when uncombined and in the presence of oxygen, is an extremely unstable salt. When in the presence of oxygen, as the air or underground waters, ferrous oxide is almost immediately oxidized, and forms ferric oxide. Ferrous oxide may be prepared by heating ferrous oxalate in the absence of air—a method not usual in rock formation—or by reduction of ferric oxide by hydrogen. As soon, however, as the hydrogen is removed and the ferrous salt exposed to air it passes back to the ferric oxide.

Contrasted sharply with ferrous oxide as to stability is ferric oxide (Fe_2O_3). It is one of the most stable compounds known. It is almost absolutely insoluble in water. Russel[2] found .00072 parts of

[1] F. W. Clarke, "Data of Geochemistry," *U. S. Geol. Surv. Bull.* 491, p. 28.

[2] I. C. Russell, "Subaerial Decay of Rocks and Origin of the Red Color of Certain Formations," *U.S. Geol. Surv. Bull.* 52, p. 38.

Al_2O_3 and Fe_2O_3 in the water of the James River, near Richmond, after flowing over the red Newark rocks to the west, as compared with .01284 parts of calcium. Calcium carbonate is a relatively insoluble salt, but compared with ferric oxide it is quite soluble.

Ferric oxide is the highest state of oxidation iron can assume in any of the processes of rock formation. On the contrary, ferrous oxide can exist but a short time as such in rock-forming processes in areas of denudation, and almost immediately passes to the ferric condition.

The foregoing statement of simple chemical facts may appear unnecessary. In its justification the writer would here call attention to a most amazing fact in connection with practically every discussion of red beds. That fact is the almost universal feeling on the part of geologists that some especially powerful source of oxidation is required to make ferric oxide. Assuming, as most of them do, that the red color is due to ferric oxide—which of course is correct—their chief concern has been to produce this ferric oxide. They have taken for granted that once ferric oxide was formed the rocks would be red. This, as will be brought out below, is not the case.

In the course of his work on the red beds the writer examined, literally, hundreds of articles on the red beds. It is safe to say that 95 per cent of the writers felt the need of unusually active oxidizing forces to form ferric oxide. Hence the frequent postulation of deserts and semi-arid climates. This feeling that red beds are somehow connected with deserts is almost universal with geologists who have not given much serious thought to the subject.

The facts, of course, are that the agencies to produce ferric oxide are everywhere present where erosion is taking place, and that it would be extremely difficult if not impossible for anything but ferric oxide to form. The agencies which form ferric oxide are the normal everyday processes of erosion. And so the writer feels justified in recalling the foregoing elementary chemical facts about ferrous and ferric oxides in the belief, incredible as it may seem, that it has been the overlooking of these simple characteristics of the two iron oxides, together with the false assumption that the mere presence of ferric oxide would make rocks red, that has led to most, if not all, of the red-bed confusion.

With these facts before us, we can repeat the question, Is the iron present in the red rocks in a form different from that in the non-red rocks?

Black New Jersey argillite contained 7.27 per cent of FeO, and 0.64 per cent of Fe_2O_3. Non-red sericitic schists from Maryland show as in Table III.

TABLE III

	1	2
	Per Cent	Per Cent
Fe_2O_3	3.19	2.62
FeO	4.87	5.63

The andesite, which Keith[1] refers to as assuming "a full red color that is very striking," has 11.17 per cent of Fe_2O_3, and 5.64 per cent of FeO. Catoctin schist contains about equal proportions of "ous" and "ic" iron.

Analyses of Maryland red rocks record only ferric iron.

Tomlinson[2] has summed up a number of analyses, and quotes from Dale[3] as shown in Table IV.

TABLE IV

	Fe_2O_3	FeO
	Per Cent	Per Cent
Red slates	5.26	1.21
Purple slates	5.30	2.15
Green slates	1.35	5.21
Black slates	0.75	5.27
Spotted slates	1.09	1.06

There is an obvious excess of "ic" iron in the reds and purples, and of "ous" iron in the green and black shales.

The same writer, Tomlinson,[4] gives the following analyses from more typical red beds:

[1] Arthur Keith, "Geology of the Catoctin Belt," *U.S. Geol. Surv., 14th Ann. Rept.*, Part II, pp. 302–3.

[2] C. W. Tomlinson, "The Origin of Red Beds," *Jour. Geol.*, Vol. XXIV, p. 160.

[3] T. Nelson Dale, "The Slate Belt of Eastern New York and Western Vermont," *U.S. Geol. Surv. 19th Ann. Rept.*, Part III, pp. 159–308.

[4] *Op. cit.*

Vernon formation, Silurian, New York.[1]

1. Red shale.
2. Green spot in red shale.

Chugwater formation, Wyoming[2]

3. Red sandstone.
4. Green sandstone, due to crushing of red sandstone along crack.

Spearfish formation, Black Hills, Wyoming[3]

5. Green shale.
6. Red shale, adjacent to green.
7. Red shale.
8. Red shale.

TABLE V

	1	2	3	4	5	6	7	8
	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent	Per Cent
Fe_2O_3	2.25	0.00	3.50	1.03	1.85	4.61	3.64	2.04
FeO	0.75	1.19	1.04	1.04	1.04	1.24	0.65	0.18

Spring[4] records the following ratios in red and green Devonian schists from Germany:

	Fe_2O_3 Per Cent
Green schist	2.98
Red schist	9.21

An excess of ferric over ferrous iron is observed in the case of the red rocks in the foregoing analyses.

However, many rocks far higher in ferric iron than the red rocks are not red. The Catoctin schist and the slaty volcanics of the foregoing analyses contain 9.44 and 11.73 per cent of Fe_2O_3, and are not red. Brown sandstone from New Jersey contains an average of 3.39 per cent Fe_2O_3, while the average of seventy-eight shales contain 4.03 per cent of Fe_2O_3. The average non-red shales of Indiana and Pennsylvania contain, respectively, 7.59 and 6.07 per cent of Fe_2O_3, while the average red Newark shale in Maryland contains

[1] *Bull. 140, N.Y. State Mus.*, pp. 150–56.

[2] E. Blackwelder, *U. S. Geol. Surv.*, Analysis 2530.

[3] G. B. Richardson, *Jour. Geol.*, Vol. XI, pp. 365–93.

[4] W. Spring, "Sur les matières colorantes, à base de fer, des terrains de sediment et sur l'origine probable des roches rouges," *Reçueil des traveaux Chimiques des Pays-Bas et de la Belgique*, Vol. XVII, pp. 202–21. Also, *Neues Jahrbuch für Min. Geol. und Pal.*, Part I (1899), pp. 47–62.

6.16 per cent of Fe_2O_3. The mere presence of ferric oxide in rocks does not make them red in color.

At this point it is interesting to make a list of the oxides of iron. These are:

Ferrous oxide, FeO, green
Ferric oxide, $Fe_2O_3 . n\ H_2O$

This ferric oxide occurs in the following sesquioxides:

Limonite—$2Fe_2O_3, 3H_2O$. Yellow, brown
Xanthosiderite—$Fe_2O_3, 2H_2O$. Golden yellow to brown
Göthite—Fe_2O_3, H_2O. Yellow, brown, brownish black
Turgite—$2Fe_2O_3, H_2O$. Red to reddish brown
Hematite—Fe_2O_3. Red

The point to be remembered about the foregoing group of sesquioxides of iron is that they are all ferric oxide. Varying in color from browns through yellows to red—in other words, through all of the most common rock colors—the members of this group of ferric oxides differ from one another only in the amount of water they contain, and in color, the yellows being at the end containing the greatest amount of water, and the reds at the anhydrous end.

It is thus apparent why a non-red rock can contain a larger amount of ferric iron than a red one—it contains iron of the limonite or hydrated type, while the red rocks contain iron of the hematite type, or dehydrated ferric oxide. It is this dehydrated ferric oxide which makes rocks red. A small amount of brilliant red pigment will color a relatively large mass of material, and will therefore appear to occupy a larger proportion of the rock material than it actually does.

At this point the whole problem as to the color of red beds is seen to shift from the question as to how ferric oxide can be formed, since ferric oxide is an almost unavoidable product in the disintegration of rocks, to the question of how hydrated ferric oxide can lose its water. We are to inquire into the processes of dehydration and not of oxidation.

The literature pertaining to the dehydration of ferric oxide is copious and convincing. In a short paper such as this no adequate review can be given of the mass of observations on the dehydration

of ferric oxide. But a striking departure is taken, when we are discussing dehydration, from all but some half-dozen or so who have considered the formation of red beds. One passes from the dazzling glare of desert and semi-desert environments into dim, moist, warm, usually forest-covered zones, which today form a belt around the world in the low latitudes. It should be borne in mind, however, that the discussion relates to the dehydration of ferric oxide, and the conditions necessary for that to take place, and not necessarily with those under which the soils containing the ferric anhydride accumulate to form rocks. It is certain that many red sediments come finally to rest under semi-arid conditions, since gypsum and salt indicate the drying up of lakes. But the place of coming to rest of sediments and where they were formed are practically never the same.

Ferric hydrate will lose its water and turn red spontaneously, if given time enough. Spring[1] calls attention to the fact that hydrated iron oxide, kept under water for several years, will lose its water and turn red. Spring concludes, "Hydrated oxide of iron is therefore not a stable body—gradually giving up its water so long as it is by itself—that is, is not in molecular combination with other oxides." The reason all of the rocks containing ferric oxide are not red, since time enough has undoubtedly elapsed in even the most recently consolidated beds to allow dehydration to occur, is probably that the ferric oxide is so bound up molecularly with other oxides, generally silica, that it is not able to continue its dehydration. Tomlinson[2] and Crosby[3] give excellent summaries of the evidence concerning dehydration.

The rate at which dehydration occurs is affected by heat. An elevation of temperature will hasten the action. In this connection it is significant to observe that the areas of red soil today are almost wholly in the tropical and subtropical zones.

Russell[4] reviews the observations of many explorers on this red color of soils in low latitudes. Thus, in Nicaragua, Belt observed immense thicknesses of residual soil, generally red in color, confined

[1] *Op. cit.*, p. 50. [2] *Op. cit.*

[3] W. O. Crosby, "On the Contrast of Color of the Soils of High and Low Latitudes," *Amer. Geologist*, Vol. VIII, p. 80.

[4] *Op. cit.*, pp. 28–29.

almost exclusively to the heavily forested regions. Gabb, on Curacao, describes the soil as a red residual limestone soil like that found in Jamaica, Santo Domingo, the Bahamas, etc. Agassiz, Liais, and Hartt record immense residual deposits of a red color in Brazil, and these are doubtless the source of the red muds which Murray[1] found in such quantities in the Atlantic Ocean off the mouth of the Amazon River. In Southeastern Europe the *terra rosea* of the Istrian Peninsula, Dalmatia, and Greece consists of red clay, residual from a limestone basement. In Spain the landscape is much like that of the southern Appalachians in appearance and composition. The laterite of Southern Asia, formed by decomposition of basalt, gneiss, etc., is a brilliant red, and gives rise to the name "Red Hills" near Madras.

Dana records similar red residual soils from basalt in Australia, Tahiti, Terra del Fuego, and in New Zealand and China. On Kerguelen and Crozet Islands, where there is a cold, humid climate with no forests, no red soil whatever is observed. The residual soils of Bermuda are brilliant red, and must owe their iron to the decay of the coral. The coral contains 0.54 per cent of Fe_2O_3 and Al_2O_3; the red earth contains 13.898 per cent of Fe_2O_3. The red Cuban and New Caledonian laterites are left by the decomposition of the underlying serpentine. In addition to these localities, all in low latitudes, the southern Appalachian region is an area which contains a large percentage of red soil. South from about the latitude of Maryland the soils which can be regarded as true residual soils are for the most part red.

The primary requisite for the dehydration of ferric hydrate is, as noted above, time. When heat is added the dehydration is accelerated, and the red hydrate (turgite) and the anhydride (hematite) form more rapidly. It should be borne in mind that the oldest soils are at the surface of the ground, and the younger lie below the surface. For this reason, where red soil is present it is at the surface, and grades downward through yellows and browns to the green colors of the ferrous oxide in the youngest soils.

The explanation of the preponderance of red soils in the warmer belts of the earth is therefore apparent. Dealing with a chemical re-

[1] J. Murray, *Deep Sea Deposits* (1891), p. 234.

action which occurs spontaneously, but which requires a definite period of time for its action, regions with characteristics which will hasten the rate and at the same time prevent the soil from being removed will be those in which red soils are most likely to be found. The entire problem resolves itself into securing enough time to allow the ferric oxide to undergo dehydration. In the warm belts the heat is present to speed up dehydration, and the heavy cover of vegetation usually present keeps the soil from being removed. In those areas either colder or with less soil-binding material in the form of vegetation, although dehydration of the ferric oxide will progress, the soil is removed by the normal processes of erosion before there has been time enough for the red oxides to form.

The conclusion seems inescapable that the red soils of which the red rocks of the earth are composed assumed their color not in deserts —which are practically never red—nor in semi-arid climates, but in warm, moist, heavily forested regions similar to the tropical and subtropical areas of the earth today.

To form red soil it is also necessary that drainage be active, since the decay of vegetation in swamps would cause reduction, the ferric oxide would be reduced to ferrous oxide, and greenish rocks would result. Alternate wetting and drying and active drainage are very powerful oxidizing forces, and will quickly burn up organic material.

The red Morrison formation of the west is an excellent example. The Morrison witnessed the greatest development of the Sauropodian dinosaurs, the largest of all dinosaurs; and, in addition, a widespread efflorescence of dinosaurian forms in general. These were very largely herbivorous. Great faunal developments are usually due to peculiarly favorable environmental conditions. Such immense forms as the Sauropods must have consumed tremendous quantities of vegetation. Mook[1] in a summary of the Morrison flora records only a few Cycadellas, questionably *Araucarioxylon obscurum* and possibly *Pinoxylon dacotense*. These remains are scattered and fragmentary. This meager flora as food for the great reptiles was wholly inadequate. Plainly there must have been a large flora present of which we have no record. In its disappearance

[1] C. C. Mook, "A Study of the Morrison Formation," *N.Y. Acad. Sci., Annals*, Vol. XXVII, p. 126.

it did not reduce the iron, since the beds are red today. Oxidation accompanying the conditions under which the flora flourished—the same conditions which permit the formation of red residual soils—burnt up fallen and dead vegetation. The great bones of the dinosaurs are for the most part fragmentary when found in the red beds proper.

3. IF COLOR IS DUE TO IRON IN DIFFERENT FORM, WHAT WERE THE PECULIAR CONDITIONS WHICH PERMITTED RETENTION OF SUCH FORM IN RED ROCKS AND NOT IN AVERAGE ROCKS?

Fortunately this question can be answered at once and with certainty.

The fate of practically all sediments, red, yellow, gray, is transportation to and deposition in the sea, on the continental shelves. Upon the continental shelves a wholesale reduction is in progress comparable in its extent and universality to the oxidizing forces at work upon the land surfaces. Since it is the fate of all marine sediments to be exposed to this gigantic reducing action, which will quickly destroy a large part of the ferric oxide, we should not expect to find true marine beds red. The sediments to retain their original red color must come to rest in an environment where they will not be exposed to reduction. Once ferric hydrate becomes red it will retain its color throughout transportation and all its future history if not reduced chemically.

Obviously, coming to rest upon continents, or in bodies of water—inland lakes, bays, etc.—where there is no widespread reduction in progress will satisfy the conditions necessary for preservation of the red color. The most common feature of the vast majority of red beds is the indisputable evidence of continental origin. Raindrop impressions, mud cracks, cross-bedding, fresh-water mollusks, footprints of terrestrial vertebrates in mud-cracked shale, plant remains, gypsum deposits, absence of indigenous petroleum in quantity—all these can mean but one thing. The beds came to rest upon a continental rather than a marine floor. And, in the light of the necessary chemical conditions, it is the only way great thicknesses of red sediments could be deposited and remain red.

When, from time to time, an unusually heavy amount of drainage took place from a continent into the oceans it is likely that the true

marine conditions—the reducing agencies—of the continental shelves would be temporarily pushed farther offshore, to return when the abnormal runoff had ceased. This would permit red sediments to appear as a wedge in a true marine series, such wedges as are actually found at many levels in the geological column. The red wedges in the Silurian of Eastern North America are examples. Here true marine brachiopods are found as fossils in a red matrix, where they had been overwhelmed by a sudden influx of abnormal amounts of continental material.

Murray[1] on the Challenger Expedition found that red continental deposits extended far out on to the continental shelf off the mouth of the Amazon River. Here the amounts of fresh water and continental sediments are so abundant as to force true marine conditions farther offshore. Such a red wedge as is referred to in the Silurian is being formed today in a true marine section off the coast of South America.

CONCLUSION

To sum up—the color of the red beds is not caused by a larger iron content than the non-red rocks. On the contrary, they often contain less iron. The color is not due merely to the presence of ferric oxide as opposed to ferrous oxide, since many non-red rocks often contain more ferric oxide than do the red rocks. The red color is caused by ferric oxide which has had time to dehydrate, and turn to the red hydrate (turgite) and the red anhydride (hematite). This dehydration takes place most rapidly, not in deserts or in a semi-arid environment, but in warm, moist climates, conditions usually productive of a heavy vegetation. By coming to rest upon continents or in other environments where large-scale reduction is not in progress, the sediments are able to retain their red color. Most sediments are carried to the seas and there, exposed to the reducing action of the decay of marine organisms, are reduced and lose their red color. Except for occasional red wedges in marine series, due to pushing offshore of the true marine environment by a temporary overwhelming influx of continental sediments, the red beds of the geological column represent continental deposits, since in deposits so formed the red ferric oxides are not subjected to reduction and thus retain their original color.

[1] *Op. cit.*

EXPERIMENTS ON THE RATE OF WEAR OF SAND GRAINS

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ABSTRACT

The experiments described in this paper were made to obtain more definite data on the relative rates of mechanical wear, on sand grains, by wind and water under constant conditions. The results show, contrary to the general belief, that sand submerged in water wears down more rapidly than dry sand transported over the same distance. From the experiments, the ratio of the rate of wear of water-transported to wind-transported sand ranges from 1.7:1 to 4.6:1. Also, the rate of wear by both wind and water, in a well-sized sand such as a dune or beach sand, is found to be very slow. Rounded or spheroidal sand grains are believed to have a longer history of rounding than could be produced in a single cycle of erosion, transportation, and deposition and probably are, even geologically, very old.

INTRODUCTION

Sand grains are characterized by certain features, which, if fully understood, would reveal much of their geologic history. Most conspicuous among these is the degree of rounding obtained through mechanical wear during transportation by either water or wind. The ratio of the rate of wear by water and wind is difficult, if not impossible, to determine from an examination of the sand grains, owing to their complex history and indeterminate origin. The distance which they may have traveled cannot be measured, because of the difficulty of tracing sand grains to their primary source.

The belief that wind is a much more efficient agency than water in the rounding of sand grains was first suggested by Phillips[1] from his microscopic study of many sand samples obtained from various geologic horizons as well as from recent dune sands from the British Coast. From Phillips' suggestion that the "millet seed" sandstone, on account of its characteristic rounded grains, might be of eolian origin, the conception developed that the wear of sand grains by water is a slow process when compared with similar wear by the wind. The latter, in fact, was regarded as sufficiently rapid to round

[1] J. A. Phillips, "On the Constitution and History of Grits and Sands," *Quart. Jour. Geol. Soc.*, Vol. III (1881), pp. 6–28.

the grains of recent dune sands in only a few miles of travel. Similar rounding of the sand grains by water was estimated by Phillips[1] from Daubree's experiments[2] to require 3,000 miles of travel (*sic*).

This conception was accepted by Klemm,[3] who studied the dunes in Germany; by Socolov,[4] who studied the Russian dunes; by Retgers,[5] who studied the dunes of Holland; and the same conclusion was reached by Mackie,[6] who studied the rounding of sand grains on the Spey River and the adjacent coast of Scotland. As the source of the sand studied by these observers is within the area of Pleistocene glaciation, this sand may have been brought in by the ice from many localities where the grains were already in various stages of rounding. Rivers such as the Spey in Scotland and the streams in the northern portion of Continental Europe have all collected sand from the same heterogeneous source.

The relative rate of wear of wind- and water-transported sand has been developed into a formula by Mackie[7] from which he concluded that wind is nearly twenty-nine times as efficient in the rounding of sand grains as is water. From the formula it is evident that Mackie considers the velocity of the transported particles to be the same as that of the transporting agency, which means that the particles are carried in suspension. In the abrasive wear of particles, by either wind or water, we are not concerned with material in suspension, where little or no wear takes place, but with the sand which is rolled forward by the wind or water. Furthermore, a wind velocity of 8 miles per hour is incompetent to move dune sand grains of average size, and a water velocity of 2 miles per hour, used in Mackie's formula, is higher than that necessary to roll the average-sized grain along the bottom of a water current.

Water has also been considered less effective than wind in the

[1] *Loc. cit.*

[2] G. A. Daubree, *Etudes Synth. de Geol. Experimentale*, 1879.

[3] G. Klemm, *Zs. deut. geol. Ges.*, Vol. XXXIV (1882), pp. 779 ff.

[4] N. A. Socolov, *Die Dunen*, Berlin, 1894.

[5] J. W. Retgers, "Über die mineralogische und chemische Zusammen-setzung der Dunensande Holland, etc.," *Neues Jahrbuch*, Part I (1895), pp. 16–74.

[6] William Mackie, "The Sand and Sandstones of Eastern Moray," *Trans. Edin. Geol. Soc.*, Vol. VII (1896), pp. 148–?

[7] "The Laws That Govern the Rounding of Sands," *ibid.*, pp. 298–311.

rounding of sand grains because of the surface tension of the film of water supposed to surround sand grains while submerged. This film, according to Goodchild,[1] serves as a cushion which prevents the grains from actually coming in contact, or at least greatly retards the force of the impact, and so proportionately reduces the rate of wear on the water-worn sand grains. However, if one submerges a layer of sand grains and touches one of them with the point of a needle held in the hand he may observe under the microscope that the sand grains act like elastic balls, due to the vibration of the hand. They collide and rebound with apparent ease, as would be expected if they were in actual collision. The film of water, if present, is apparently not competent to prevent collision. Furthermore, it has been pointed out to the writer by Professor W. D. MacMillan that sand grains submerged in water cannot be regarded as surrounded by a film differentiated from the body of the water, and that the water will not prevent collision of the sand grains while submerged.

Mackie[2] attempted to determine the rate of wear of sand grains in water, by measuring the travel distance required to round the grains, in the Spey River and other streams on the Scottish coast. His results for water rounding varied from 5 to 70 miles. From experiments similar to Daubree's, Galloway[3] concluded that it would require about 800 miles to round quartz grains. His experiments were run at a velocity of 4 miles per hour, which is probably considerably higher than the average rate attained in nature. That rapid rotation reduces material very quickly is amply proved by the ball mill. No estimates of the distance required to round sand grains by the wind have been given, though generally it has been regarded as running into a few miles or even less. Knight[4] by blowing quartz fragments 1–2 millimeters in diameter at a velocity of 40 miles per hour, succeeded in reducing these grains to $\frac{1}{2}$ millimeter, in a distance of 50 miles. This seems a higher velocity than that necessary to roll sand grains of average size common in dunes, and at such ve-

[1] J. G. Goodchild, "Desert Conditions in Britain," *ibid.*, pp. 203–22.

[2] *Loc. cit.*

[3] J. J. Galloway, "On the Rounding of Sand Grains by Solutions," *Amer. Jour. Sci.* (4), Vol. XLVII, pp. 270–80.

[4] S. H. Knight, *Geol. Soc. Amer.*, Vol. XXXV, p. 107.

locity these will be carried in suspension when abrasion is a minor factor.

Precise data for the relative rate of abrasion of either wind- or water-worn sand are thus almost entirely lacking. Particularly is this true for the rounding of sand grains in eolian transportation. The reason for this is obvious. The wind may pick up and deposit sand, irrespective of topography and altitude, rendering the tracing of the wind-carried sand indefinite. To determine the relative rates of wear by water and wind, laboratory experiments are here used under certain fixed conditions. While limited in scope, the experiments supply data which are believed to contribute to the solution of this problem.

EXPERIMENT I

Samples of the same sand were run in pairs, of which one was dry while the other was submerged in water, and rotated by means of the tumbling barrel. The samples were taken from river and dune sands on the Canadian River, near Norman, Oklahoma. These were carefully mixed, quartered down to proper size, and opposite corners taken—one for the dry, the other for the wet sample. Distilled water was used in the ratio of four volumes of water to one of sand. The weight of sand used in each sample was 70 grams. The samples were put in glass bottles of 3-inch diameter and provided with ground-glass stoppers. The bottles were then placed in the tumbling barrel and rotated at a velocity of $\frac{1}{2}$-mile per hour, which was continued for a travel distance of 190 miles. They were then decanted, evaporated to dryness in an electric oven, and screened by a mechanical shaker for twelve minutes and each screen product weighed. Tyler standard screens were used of the following mesh:

Mesh	Size in Millimeters
14	1.168
20	.833
28	.589
48	.295
100	.147
150	.104
200	.074
Through 200 less than	.074 (pan)

Samples Nos. 1, 2, 3, and 4 are dune sand from the same sample. To Nos. 3 and 4 were added approximately 10 grams of quartz pebbles of $\frac{1}{8}$ inch diameter. Samples 5, 6, 7, and 8 are coarser products screened from river sand. In the tables, the odd number refers to the dry sample while the following even number refers to the same sand run in water. Thus Nos. 1 and 2 are the same sand, etc. The data are tabulated showing the weight in grams retained on each screen at the end of the run. These weights are also converted to cumulative percentages, in Nos. 1–4, for direct comparison. The results are shown in Table I:

TABLE I

Mesh	14	28	48	100	150	200	Pan
No. 1, dry	.....	.....	.70	40.87	19.27	6.17	1.56
No. 2, in water	.....	.....	.80	39.15	19.86	6.15	2.20
Cumulative percentage, No. 1	.....	.....	1.1	61.0	89.5	98.6	.....
Cumulative percentage, No. 2	.....	.....	1.2	58.0	87.0	96.0	.....
No. 3, dry	.....	.....	.47	35.75	19.38	6.10	2.78
No. 4, in water	.....	.....	.55	33.35	18.49	7.27	5.37
Cumulative percentage, No. 3	.....	.....	.66	56.5	87.0	96.0	.....
Cumulative percentage, No. 4	.....	.....	.75	52.0	80.6	90.0	.....
No. 5, dry	31.70	35.53	.29	.55	.12	.029	.050
No. 6, in water	23.79	41.93	.535	.40	.13	.030	.030
No. 7, dry	67.37	.678	.359	.34	.11	.03	.055
No. 8, in water	65.94	.640	.355	.37	.105	.035	.080

By comparison of the corresponding screen products, it should be noted that the reduction to finer size is more rapid in the water-worn sand, the only exceptions being the 48-mesh products of Nos. 1 and 3. Both these products are small, representing but 1 and $\frac{1}{2}$ per cent, respectively, of the total weight of the samples. By comparing the cumulative percentages, the results are shown to be strikingly in favor of the water-worn sand. In the presence of pebbles the rate of reduction is considerably increased in both the dry and the water-worn sand and with an appreciable increase in the rate of reduction for the water-worn sand. The greater amount of fines in the presence of the pebbles is not due to loss suffered by the pebbles, for this loss is very slight. Thus out of approximately 10 grams of pebbles, the

loss due to wear of the pebbles was .019 grams for the dry sand and .024 for the water-worn sand. It seems probable, therefore, that the pebbles have served as grinders among the finer sand grains, crushing and fracturing these, and thus reducing the sand to smaller grains though more angular in outline. The same process is at work in all streams where coarser fragments are always present. Only a very few sand grains in the total volume transported by the stream may indeed escape being crushed between larger fragments so long as the latter are present and can be moved by the maximum floods of the stream. It should also be noted that in the water-worn samples some material goes into solution or a colloidal condition, or remains mechanically suspended in the decanted water. While this is probably small, it tends to reduce the weight of the pan product in the water-worn sand.

EXPERIMENT II

In this series of experiments, an oscillating agitator was used. The agitator has a forward-and-back motion in a horizontal position, of $3\frac{1}{2}$-inch stroke, and a velocity of one hundred and fifty strokes per minute. The agitation of the grains set up by the mechanism is similar in intensity to wave-tossed sand in the churning water of the beach during a storm, or the agitation of the wind-carried sand during a desert dust storm. A frame with space for eight bottles is attached to the mechanism. It is actuated by a small motor. Eight samples were run at a time in pairs as in the earlier experiment. Four different sands were thus run. Of each pair one was dry, while the other one at its side was run in four volumes of distilled water. All the samples were 25 grams in weight.

The samples were obtained as in the earlier experiment by quartering, and initial screened products weighed. The experiment was run in 120-hour intervals. At the end of each interval, the screened products were weighed. The samples were obtained from the Atlantic beach at Nahant, Massachusetts; from the Pacific beach about 5 miles north of Huntington Beach, California; from river dunes on the east side of the Rio Grande, 5 miles north of Socorro, New Mexico; and from a Columbia River dune at Rowena, Ore. The tabulated results of the screen analyses are as shown in Table II.

TABLE II

Mesh	48	100	150	200	Pan	Grams Total
	Nos. 9–10, Atlantic Beach Sand					
No. 9, dry:						
Original	.02	14.53	9.80	.61	.04	25.00
120 hours	.02	14.49	9.56	.59	.04	24.70
240 hours	.03	13.65	10.38	.67	.05	24.78
Net change in weight	.....	.87	.31	.24	.06	.....
Percentage of original of this screen product	.....	6.0	3.	40.	150.0	.....
No. 10, in water:						
Original	.02	14.59	9.69	.59	.05	24.95
120 hours	.015	14.57	9.42	.60	.08	24.69
240 hours	.015	13.44	10.40	.65	.11	24.61
Net change in weight	.....	1.15	.44	.38	.09	.....
Percentage of original of this screen product	.....	8.1	5.	64.	180.	.....
	Nos. 11–12 Huntington Beach, Calif., Sand					
No. 11, dry:						
Original	4.94	17.97	1.74	.18	.03	24.87
120 hours	4.96	17.90	1.74	.27	.04	24.90
240 hours	5.09	17.70	1.73	.29	.04	24.85
370 hours	5.04	17.62	1.76	.32	.05	24.79
Net volume change in weight	.10	.25	.23	.09	.....	.....
Percentage of original of this screen product	2.	1.2	13.	50.	.....	.....
No. 12, in water:						
Original	4.45	18.65	1.59	.15	.03	24.87
120 hours	4.42	18.50	1.59	.20	.02	.....
240 hours	4.40	18.43	1.64	.26	.05	24.78
370 hours	4.35	18.23	1.68	.24	.05	24.55
Net change in weight	.10	.52	.43	.34	.....	.....
Percentage of original screen product	2.	3.	29.	229.	.....	.....
	Nos. 13–14, Socorro, N.M. Rio Grande Dune Sand					
No. 13, dry:						
Original, .015	6.01	12.91	2.54	1.69	1.79	25.09
120 hours, .02	6.35	12.63	2.47	1.67	1.72	24.86
240 hours	6.09	12.82	2.40	1.63	1.75	24.69
Net change in weight	.06	.03	.17	.23	.....	.....
Percentage of original of the screen product	.....	.75	6.6	13.	.....	.....
No. 14, in water:						
Original, .15	6.00	14.25	2.25	1.34	1.08	24.94
120 hours	.....	.....	.....	.....	.....	.....
240 hours	5.78	13.46	2.37	1.24	.80 1.03	24.68
Net change in weight	.37	1.16	1.04	1.14	.....	.....
Percentage of original of this screen product	6.	8.3	46.4	86.	.....	.....

TABLE II—*Continued*

Mesh	48	100	150	200	Pan	Grams Total
	Nos. 15-16, Columbia River Dune Sand					
No 15, dry:						
Original, .03	3.12	16.17	3.51	1.49	.67	24.98
120 hours	3.73	15.51	3.55	1.46	.66	24.91
240 hours	3.65	15.30	3.68	1.45	.65	24.73
370 hours	3.54	15.46	3.55	1.47	.67	24.69
Net weight in change	.....	.71	.67	.69	.....	.....
Percentage of original of this screen product	.....	4.4	16.	41.	.....	.....
No. 16, in water:						
Original, .03	2.94	15.77	3.74	1.65	.80	24.93
120 hours	.....	.....	.....	.....	.....	.....
240 hours, .03	3.04	14.90	3.79	1.57	.78 / .67	24.78
370 hours, .01	2.72	14.89	3.78	1.59	.79	24.73
Net change in weight	.24	1.12	1.08	1.06	.....	.....
Percentage of original of this screen product	8.1	7.7	29.	61.	.....	.....

ANALYSES OF THE SCREEN PRODUCTS

Immediately under the final weights in Table II of the screen products will be found the net change in weight of each screen product, which represents the calculated weight of sand which has passed each screen. This is obtained by adding the loss in the initial screen to the initial product of the next screen, and by deducting from this sum the final product of the latter screen. Thus, in No. 9 the final product in the 48-mesh screen is 03. gram. This is added to the initial product of the 100-mesh screen, which is 14.53 grams. From their sum (.03+14.53=14.56) is subtracted the final product in the 100-mesh screen, or 14.56−13.65=.89 gram. This represents the total passing the 100-mesh screen. This is then added to 9.80, the initial product of the 150-mesh screen, and from the sum is subtracted 10.38, the final product in this screen. Thus, .89+9.80=10.69−10.38=.31, the product passing the 150-mesh screen. The remainder thus obtained is the net change in weight during the experiment, for each screen. This affords a direct means, not only of accurately determining the change which has taken place in the particular screen, but also of comparing the net change in weight with the corresponding screen product of the other member of the pair of samples. In

order to make the comparison more clear, the numbers have been reduced to percentages of the original weight of the sample retained on this particular screen, which then admits of direct computation of the relative rate of wear of the corresponding product of the two samples, where comparison is desired, as in samples 9 and 10 (of the same sand), etc. These percentages and the ratios based upon them are as shown in Table III:

By comparison of the weight ratios of No. 9 to No. 10, it will be noted that 1.3 times as much material passed the 100-mesh screen

TABLE III

Mesh	100	150	200
No. 9, percentage of change in weight	6.0	3.0	40
No. 10, percentage of change in weight	8.1	5.0	64
Change in weight ratio, No. 9:No. 10	1:1.3	1:1.66	1:1.6
No. 11, percentage of change in weight	1.2	13	50
No. 12, percentage of change in weight	3.0	29	229
Change in weight ration, No. 11:No. 12	1:2.5	1:2.2	1:4.6
No. 13, percentage of change in weight	.75	6.6	13.0
No. 14, percentage of change in weight	8.3	46.4	86.0
Change in weight ratio, No. 13:No. 14	1:11	1:7	1:6.6
No. 15, percentage of change in weight	4.4	16.0	41.0
No. 16, percentage of change in weight	7.7	29.0	61.0
Change in weight ratio, No. 15:No. 16	1:1.7	1:1.8	1:1.5

of No. 10 as of No. 9, etc. Similarly in all the screen products, the ratios indicate a greater volume of water-worn sand passing any particular screen than of wind-worn sand.

SOURCES OF ERROR IN THE EXPERIMENTS

1. It is impossible to eliminate a small amount of mixing of the samples through the screens, as a few grains are so caught in the screen that they cannot be removed without injury to the screen or undue loss of time. The products were all carefully removed by wire and root brushes, and the samples of the same sand were run through together in order to eliminate as far as possible mixing with other sand.

2. It is conceivable that some sand grains have adhered to the brush and in that way found their way into the next sample.

3. In the water-worn sand, some material undoubtedly passed into solution, and some was so fine as to remain in suspension even after hours of settling. Such losses do not appear in the weighed products in the pan, which will be low to that extent.

4. The losses necessarily involved in the transfer of the products from containers to evaporating dishes, from these to the screens, and then to the scales and back to containers for each product of the sample gradually reduces the total weight of the sample.

5. In the experiments a uniform velocity has been used, while in wind-blown material changes of velocity are common and sometimes very great. An attempt has been made to confine the velocity to such a rate as is competent to move sand grains of common size. The velocity has not been changed for samples of coarser grains, as all samples were run in a single unit. A higher velocity than that necessary for the actual rolling of the sand grains in a current of water, it is believed, will unduly increase the rate of reduction into fines, as seems already proved by the ball mill.

GEOLOGIC SIGNIFICANCE OF THE EXPERIMENTS

Grains of soft minerals such as gypsum, calcite, mica, etc., have been observed by Walthers,[1] Beadnell,[2] Retgers,[3] and others as common constituents of desert and beach dunes. Dune deposits composed entirely of such softer minerals are also known. Gypsum dunes, covering an area of 350 square miles and 14 feet deep have been described from New Mexico by Herrick[4] and from Utah by Gilbert.[5] In the latter locality the dunes are composed of small gypsum crystals with well-preserved crystal faces. While such crystals may not have traveled far, they are located in an arid region where high wind velocity is common. Dunes of lime granules are known in the Bahamas and the Bermudas, and also reported from

[1] J. Walthers, "Die Denudation in der Wuste," *Abh. d. K. Sach. Gesel. d. Wiss.*, Vol. XVI, 1890.

[2] H. J. L. Beadnell, "The Sand Dunes of the Libyan Desert," *Geog. Jour.*, Vol. XXXV, pp. 379–95.

[3] *Loc. cit.*

[4] C. L. Herrick, "Geology of the White Sands of New Mexico," *Jour. Geol.*, Vol. VIII, p. 112.

[5] G. K. Gilbert, "Gypsum Sand, Sevier Valley, Utah," *Mono. 1, U.S.G.S.*, p. 332.

India by Evans.[1] In the latter case the sands are found 30 miles from the sea and form a deposit 200 feet in thickness, resting on the Deccan trap. The lime granules were examined microscopically by Chapman and found to contain calcareous particles derived from shallow-water marine organisms of recent types. Other similar occurrences are noted by the same writer on the coast of Kathwar, 6 miles from the sea, and by Carter[2] on the coast of Arabia where high dunes of lime granules cover extensive areas inland. Apparently, in these cases, the gypsum and lime granules survive the mechanical wear of the wind.

Furthermore, deposits of desert dunes are not always characterized by rounded sand grains. The Takla Makan Desert which, according to Hedin,[3] occupies an area of 470,000 square kilometers of which 370,000 square kilometers is covered to an average depth of 50 meters. The volume of sand in this desert is estimated at 4,000 cubic kilometers and is the largest single body of desert dune sand in the world, according to the same writer. The desert is surrounded by mountains: the Tian Shan on the north, the Hindu Kush on the west, and the edge of the Tibetan Platea upon the south. Only to the east is the basin open between the high mountain ranges. The west end of the desert is about 900 feet higher than the east end. Streams drain into the basin from the high mountains, and flowing easterly along the margins of the desert, carry the sand with them to the east end. Here the prevailing easterly winds drive the sand westerly across the desert in large dunes. This is therefore an ideal situation for the rounding of sand grains by the wind, for the sand may thus repeat the journey across the desert again and again. Out of eight samples collected by Hedin, from widely separated localities, only two contained rounded grains, the others being characteristically angular.

Also, the nature of the formation of dunes is such that the wind is in reality given little opportunity to round the sand grains, for

[1] J. W. Evans, "Mechanically Formed Limestones from Junagarh (Kathiawar) and Other Localities," *Quart. Jour. Geol. Soc.*, Vol. LVI, pp. 559–83.

[2] H. J. Carter, *Jour. Bombay Branch Roy. Asiatic Soc.*, Vol. III, Part I (1849), p. 158.

[3] S. Hedin, *Scientific Results of a Journey through Central Asia*, Vols. I and II.

only a very thin surficial portion of the dune is exposed to the wind action at any one time, while the entire mass of the dune below is at rest. Only a complete overturn of the entire dune will afford the wind an opportunity to roll all the grains of the dune. As the rate of travel of the dune is proportional to its mass, it is evident that the overturn of large dunes may require a very long time, running into centuries. This is shown by the fact that large dunes in the Sahara Desert have been used as landmarks in some instances for over one hundred years.

The sorting action of the wind, according to Udden, results in the formation of four products, namely, lag gravel, which represents the coarse residuum which the wind is incompetent to transport, also called "desert pavement" by Tolman;[1] the drifting sand which is rolled along the surface by the wind and forms dunes, the fine sands, which accumulates on the lee side of the dune, called "lee sand"; and, finally, dust or the fine materials which are taken into suspension by the wind and become dispersed, possibly contributing to the formation of loess.

Only material of the second and third classes above will be formed into dunes by the wind. These are the only products, in fact, which can be rolled or saltated by the wind, and hence are the only products subject to rounding. It will require a certain velocity of the wind to set the grains into a rolling motion, which is known as the "first critical velocity," and a certain higher velocity at which the grains will go into suspension, known as the "second critical velocity." The first critical velocity for dune sand has been determined by the writer at approximately 10 miles per hour. The second critical velocity is about 20 miles per hour, for at a higher velocity the sand moves *en masse* and goes into suspension. At wind velocities between 10 and 20 miles the sand is rolled forward over the surface, but not at the same velocity as the wind, for the sand drags behind and may never reach a velocity of more than 4 or 5 miles per hour, but more commonly 1 and 2 miles per hour. The degree of rounding of the individual grains will largely determine the velocity at which the sand grains will be rolled or saltated forward, as well as

[1] C. F. Tolman, "Limitation of Scour by Boulder Pavements," *Jour. Geol.*, Vol. XVII, pp. 149–51.

the character of the surface, etc. The rounding of the sand grains by the wind will therefore be limited to wind velocities ranging between 10 and 20 miles per hour upon the gound.

It has been shown by several observers that the wind velocity increases rapidly with distance above the ground. Thus it was found by Cressey[1] that at 131 feet, the height of the wind cups at the Rosenwald Station of the University of Chicago, as compared with the ground on the Midway near by, the wind velocity was in the ratio of 1:.275, or little more than one-fourth, and that at 10 to 1 foot above ground the ratio was 1:486, or less than one-half. Even at very short distances above the surface, the wind velocity is considerably increased. Thus in an air current produced by an electric fan, the writer found the ratio of wind velocity at 1 foot above a canvass-covered surface to that on the surface was 1:00:.90. At a wind velocity of 10 miles per hour on the surface of the ground, which is the minimum required to roll dune sand, we have the following calculated velocities at given altitudes:

	Miles per Hour
131 ft. above ground	36.37
10 ft. above ground	20.56
1 ft. above ground	11.11
On the ground	10.00

The figures suggest the comparatively high velocities above ground necessary to move sand on the ground. If the wind cups, for example, are 10 feet above the ground, the wind velocity at that point required to roll sand on the ground is more than 20 miles per hour. It is obvious that the wind mileage as recorded in weather-bureau observations is considerably higher for a given area than on the surface of the ground at that locality. From an inspection of station records, taking into account the altitude at which they have been taken, it becomes evident that the wind velocity is seldom sufficiently high to roll average-sized sand grains, and that such periods are of comparatively short duration.

CONCLUSIONS

While the conclusions obtained from the experiments are to be regarded as provisional, they may be summarized as follows:

[1] G. B. Cressey, Ph.D. thesis, University of Chicago.

1. The rounding of sand grains by mechanical wear is an exceedingly slow process. The wear has been much less than was suspected.

2. It is believed that water is a more effective agency in rounding beach and dune sand than is the wind when it rolls dry sand over the same distance.

3. From the slow rate of reduction which has taken place, it does not appear likely that sand grains in a single journey from the central part of a continent to the sea would experience sufficient wear to become rounded. In order to become rounded by either wind or water, sand grains must probably make several such journeys, through more than one cycle of erosion, transportation, and deposition.

4. It follows that sand grains approaching spherical shape may be of very considerable age. No such grains should be regarded as having been derived from their primary source, the igneous rocks, during the present cycle of deposition.

5. In order that any sand, or sandstone, may be made up of a great number of rounded grains so as to make this a characteristic feature, it is necessary that the sand grains become isolated from comparatively coarse materials, for coarse materials, if present, will serve as grinders and eventually fracture the grains and thereby increase their angularity. Dune and beach sands are the result of such isolation or sorting by the wind, or by the water of the beach.

6. Whatever rounding takes place while sand is in transit in the streams will be destroyed to a very large extent by the grinding and fracturing action of the coarse materials. This results in angular grains. The gathering grounds for rounded grains are therefore the beach and the dune areas.

7. The presence of a greater degree of rounding of grains, as well as a larger number of rounded grains, in recent dunes than on the beach is due to the selective sorting of the wind. Many of the grains in recent dune sand are equidimensional with hackly surfaces. Such grains, as well as the rounded grains, are rolled more easily by the wind than the angular and flattish grains which are left on the beach or in the river flats.

8. Submerged sand grains along the beach are in constant mo-

tion and are free to collide, for the film of water which has been supposed to surround such grains is either non-existent or is not sufficiently strong to prevent the collision of grains of such size as are found to be rounded in nature. The beach therefore presents the ideal situation for the rounding of sand grains.

9. Dune sands are in motion only periodically, at comparatively long intervals and then only a small surficial portion, representing but a small part of 1 per cent of the total volume of the dune, and are rounded by the wind only when the ground velocity of the wind exceeds 10 miles per hour.

POST-CINCINNATIAN GRANITES OF NORTHEASTERN PIEDMONT VIRGINIA[1]

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ABSTRACT

This paper summarizes some of the results of a geologic investigation of parts of Culpeper, Fairfax, Fauquier, Orange, Prince William, Spotsylvania, and Stafford counties in the northeastern Piedmont of Virginia. During the course of the investigation evidence was found which is believed to indicate that certain of the igneous rocks of the district are younger than Cincinnatian. The presentation of this evidence is the purpose of the present paper.

GENERAL FEATURES OF THE REGION

The area under discussion is a part of the Piedmont Uplands Province which extends entirely through the state of Virginia be-

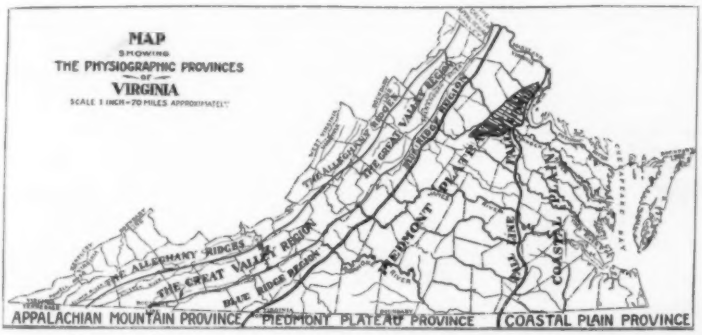

FIG. 1.—Index map showing location of area (shaded). Base after Watson, *Mineral Resources of Virginia*, 1907, p. 2.

tween the Blue Ridge and the Coastal Plain (see Fig. 1). In this belt slight relief, well-developed drainage, and great depths of residual rock decay are common. The general surface is gently roll-

[1] Published with the permission of the Director of the Virginia Geological Survey. The complete paper with a geologic map is on file in the University of Virginia Library.

ing and constitutes a partially dissected peneplain of Tertiary age. The streams, the most important of which are Potomac, Rappahannock, and Rapidan rivers, flow in general toward the southeast at right angles to the strike of the rocks formations. Due to the great depths of rock decay fresh exposures are limited to the stream valleys and the few quarries which have been opened.

THE ROCKS OF THE DISTRICT

The rocks of the district are predominantly crystalline. They include igneous and metamorphic varieties ranging from pre-Cambrian to Triassic in age. The area is flanked on the east and west by Coastal Plain sediments on the one side and Triassic red beds on the other, but these formations are of no importance in the present discussion. Among the crystalline varieties certain of the granitic rocks and the Quantico Slate are important here and will be discussed in some detail. Other crystalline types encountered will merely be mentioned. The distribution of the different rock types is shown in Figure 2 in so far as the scale employed will permit.

METAMORPHIC ROCKS

Schists of several varieties constitute the most abundant rock type of the area, forming a base into which many of the igneous masses have been intruded. The principal type corresponds to quartz-sericite schist but there are numerous others. In addition to the schists, amphibolite, soapstone, arkosic quartzite, and the Quantico Slate also occur.

The plane of schistosity of these rocks dips at high angles usually to the east while the strike is in the northeast quadrant. This condition has been the controlling structural factor of the district. Even the igneous rocks intrusive into the metamorphic rocks conform in a general way to this structure and are found in long narrow belts in a northeast-southwest direction.

The several types of schists mentioned above include both pre-Cambrian and lower Cambrian representatives. In some Piedmont localities the association of the schists with Cambrian quartzite establishes their age. In Louisa County immediately south of the area considered here a remarkable occurrence of Cambrian fossils

in the schists has been observed.[1] In the district covered by this paper it is not possible to separate the pre-Cambrian from the Cam-

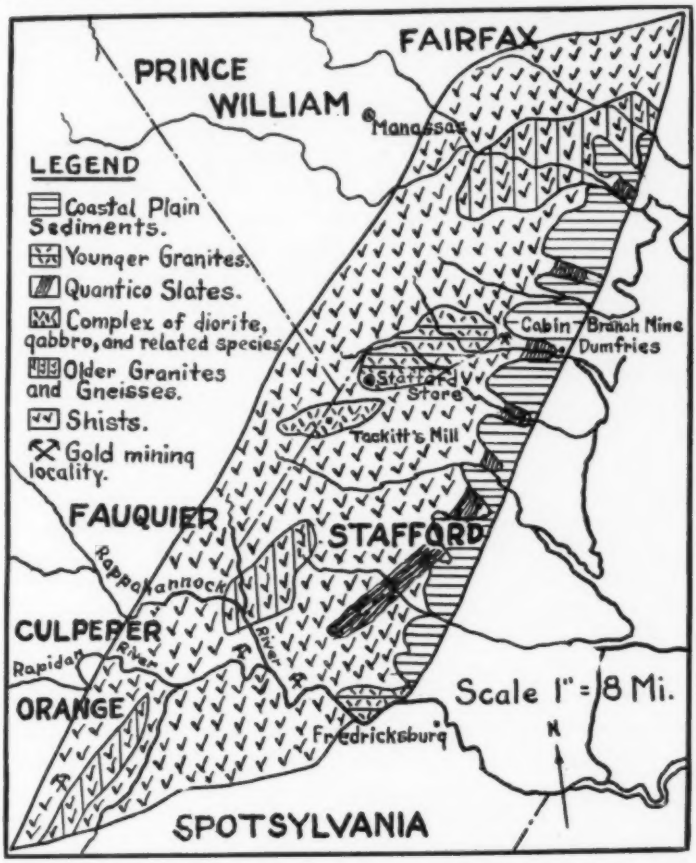

FIG. 2.—Generalized geologic map of northeastern Virginia, showing the main geologic features.

brian occurrences. The fact that the known Cambrian schist of Louisa County lies in the same strike at no great distance strongly suggests that most of the schist of this district is also of Cambrian age.

[1] Thomas L. Watson, oral communication.

QUANTICO SLATE

The Quantico Slate was separated and mapped by Darton.[1] It occurs in a narrow discontinuous belt, rarely more than one mile wide, extending for more than forty miles in a northeast-southwest direction along the eastern border of the district. Reference to Figure 2 will show its approximate location. This formation is known to be of Cincinnatian age through the work of Watson and Powell.[2] Their investigations revealed the presence of a Cincinnatian fauna in the Powell's Creek section near Dumfries in Prince William County. The importance of this formation is apparent when it is realized that, excepting the Cambrian schist mentioned above, no other established Paleozoic formation is present in the district.

The slate varies from a black graphitic variety to a gray type closely related to phyllite. Certain sections contain material which is of pyroclastic origin as shown by the presence of glass, but the greater part is terrigenous. Near Dumfries, as shown in Figure 3, unmetamorphosed granite stringers are found intruding the slate. These apparently correspond closely to aplite but are so highly weathered that an exact determination cannot be made.

The cleavage of the slate lies in the general structure of the region as previously described. In this respect it resembles the schist and other metamorphic varieties and has shared in the diastrophism to which the region has been subjected.

IGNEOUS ROCKS

Igneous rocks occurring in the district in mappable units include several bodies of granite, quartz-diorite, quartz-monzonite, rhyolite, rhyolite-porphyry, diorite, diabase, gabbro, and related more basic types ranging in age from pre-Cambrian to Triassic. Reference to Figure 2 will show the distribution of the more important of these. In the discussion to follow only granitic types will be considered.

GRANITES

The granitic rocks of the region can be divided into three groups on the basis of the degree of metamorphism exhibited by them. One

[1] N. H. Darton, *Folio No. 13, U.S.G.S.* (1894), p. 4.

[2] Thomas L. Watson and S. L. Powell, "Fossil Evidence of the Age of the Virginia Piedmont Slates," *Amer. Jour. Sci.*, Vol. XXXI (1911), pp. 33–44.

group consisting of gneisses of undoubted pre-Cambrian age is well shown in quarries in the northwest part of Fredericksburg. The rock as found at this place is medium to coarse grained with highly developed gneissic texture. Another group shows evidence of meta-

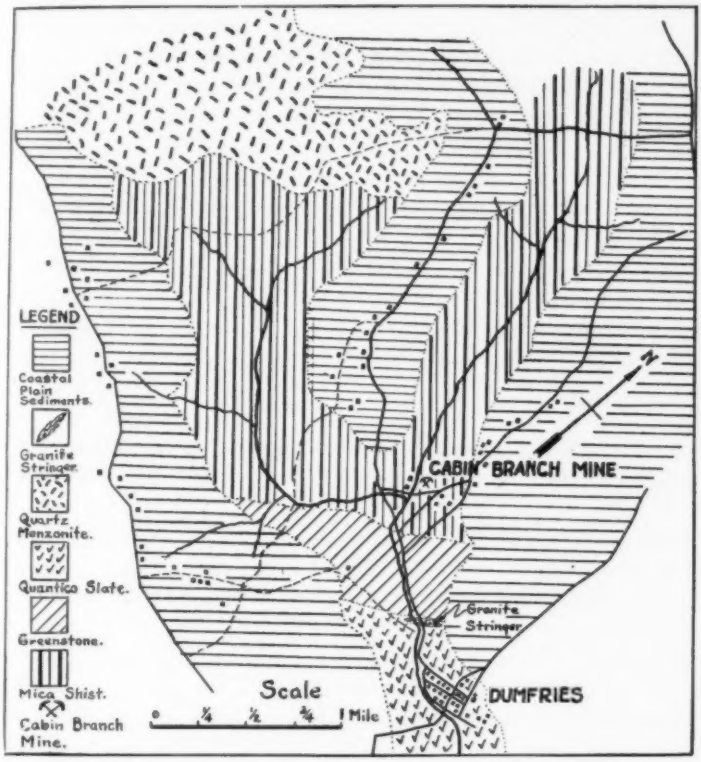

FIG. 3.—Geologic map of the area about the Cabin Branch Mine

morphism but not to the same extent as the first. There is present no highly developed gneissic texture but only a slight banding or foliation and orientation of the minerals. In some cases even the banding is not apparent in fresh specimens but is revealed only through weathering. An example of this type of granite is found one mile east

of Locust Grove in Orange County on the Orange-Fredericksburg Pike. Certain bodies of this type are found to intrude the schist mentioned above and also the gneiss. They are accordingly thought to be younger than pre-Cambrian or at the oldest not older than late pre-Cambrian.

The third type consists of rocks near quartz-monzonite which are entirely massive and which exhibit no evidence of metamorphism. They are at once seen to be younger than either of the types mentioned above and are believed to be even younger than Cincinnatian.

These three systems of Piedmont igneous rocks have been described by Watson,[1] who pointed out the facts mentioned above and called attention to their correspondence to quartz-monzonite rather than granite. They are known to occur generally throughout the Piedmont region, and in quarries in the city of Richmond all three types can be seen. It has generally been held that the gneisses and perhaps the banded granites are of pre-Cambrian age. The age of the third group has never been definitely determined.

YOUNGER GRANITIC ROCKS

Rocks belonging to the third group mentioned above have been mapped in two localities in this district. One is along Rappahannock River near Fredericksburg. Here in quarries the rock is well shown invading the pre-Cambrian gneiss from which it cannot be separated areally. The other locality is centered about Stafford Store in Stafford County. Good exposures of the rock are to be seen at Bellfair Post Office five miles east of Stafford Store.

Analyses of specimens from the two localities are given in Table I.

Chemically the two rocks are fairly close together. In the hand specimen they cannot be distinguished. Both contain feldspar, quartz, muscovite, and biotite as the essential minerals. The feldspar in both cases includes orthoclase and plagioclase near oligoclase-andesine. Thus both rocks are seen to be near quartz-monzonite in composition.

In these rocks no evidence, whatever, of metamorphism is seen. In exposures, both fresh and weathered, there is no indication of

[1] Thomas L. Watson, "Granites of the Southeastern Atlantic States," *Bull. 426, U.S.G.S.* (1910), pp. 82–88.

banding or foliation. Under the microscope the same is true. It seems certain that these rocks were not involved in the metamorphism which produced the gneiss and the foliated granite.

AGE OF THE YOUNGER GRANITES

Igneous rocks of the type described above are believed to be younger than the Quantico Slate and accordingly younger than Cincinnatian. The evidence is largely of an indirect but nevertheless convincing nature.

TABLE I

	I*	II†
SiO_2	62.63	69.48
Al_2O_3	17.63	13.95
Fe_2O_3	1.44	2.82
FeO	4.25	1.70
MgO	1.81	1.10
CaO	2.18	2.81
Na_2O	2.59	3.65
K_2O	3.77	3.45
MnO	0.08	0.03
TiO_2	1.37	0.47
CO_2	0.59	Trace
H_2O (comb.)	1.30	0.54
P_2O_5	0.31	0.49
	99.95	100.49

*Quartz-monzonite from Bellfair P.O., Stafford County, Virginia, Penniman and Brown Analysts.

†Blue gray granite from Cartwright and Davis Quarry, Fredericksburg, Virginia, W. M. Thornton, Jr., Analyst. *Bull. 426, U.S.G.S.* (1910), p. 72.

In the first place these rocks purely on the basis of physical appearance are younger than the slightly foliated granites which in turn intrude schists not older than late pre-Cambrian. In the second place the younger granite as seen around Stafford Store is entirely massive without evidence of metamorphism, while the Quantico Slate, outcrops of which are less than two miles distant, is highly metamorphosed. The field relationship of the two rocks is shown in Figure 3. It is inferred that the granite was not subjected to the deformation which yielded slate since it exhibits no metamorphic characters. It is realized that the question of relative competence of the two rocks is involved. If a granite is competent to withstand

completely the forces which yield slate and phyllite, then the evidence presented here is questionable. It is thought, however, that under such conditions the granite would show at least some slight evidence of metamorphism.

Finally, in the slate near Dumfries, two miles from the nearest exposure of granite the slate is intruded by granitic stringers. There is no direct connection between the stringers and the granite proper, but there is no other visible rock body to which they may be related. Even though they are dikes from a buried igneous mass it is still true that igneous activity occurred in the Piedmont after Cincinnatian times. It seems reasonable to assume that the stringers are related to the body of massive igneous rock whose nearest exposure is only two miles distant. If such is the true relationship the parent mass is post-Cincinnatian in age.

A NOTABLE TYPE PLEISTOCENE SECTION: THE FARM CREEK EXPOSURE NEAR PEORIA, ILLINOIS

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ABSTRACT

In 1920 a detailed examination was made by the writer of the so-called "Farm Creek Exposure" near Peoria, Illinois, from personal interest. It developed, however, that the description previously published of this very important Pleistocene exposure was considerably generalized and was made prior to our present conceptions of such materials as loess and gumbotil. The following discussion gives in detail the various elements in the section and offers an interpretation of them.

INTRODUCTION

The Peorian interglacial stage was named by Leverett[1] on the basis of the relations of a body of loess to the Illinoian and Wisconsin drift sheets in certain exposures east of Peoria, Illinois. One of these was a stream-cut exposure along Farm Creek, 7 miles east of Peoria, and another a railway cut along the Toledo, Peoria & Western Railway, about half a mile farther east. Photographs of these cuts, taken by Dr. Calvin in 1897, are shown on Plate XI of Monograph XXXVIII, opposite page 128, and general descriptions are given in the legends and on pages 128 and 187; but, to the writer's knowledge, no detailed description has been published, such as is desirable for type cuts.

In connection with his investigations of the Pleistocene for the *Illinois State Geological Survey*, the writer had occasion to visit these exposures during the field season of 1920. He was accompanied by Messrs. Ben Herzberg and E. W. Ahern, students of the University of Chicago, who aided materially in the examination. The railway cut was too badly slumped and grassed over for study, but the Farm Creek exposure was in exceptionally good

[1] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey*, Monograph XXXVIII (1899), p. 187.

condition for inspection. Because of the exceptional phenomena shown, some of which have not heretofore been noted, a detailed description was made, which will be presented and discussed herewith.

LOCATION

So far as can be determined from the post-office map of Tazewell County, the Farm Creek exposure is located near the south line of the SE. $\frac{1}{4}$, Sec. 30, T. 26 N., R. 3 W., on the south side of the stream and just east of the Toledo, Peoria & Western Railway bridge. The

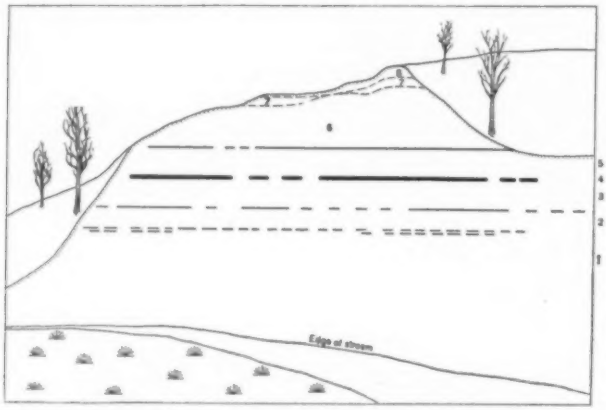

FIG. 1.—Diagram of the stratigraphic successions at the Farm Creek exposures. (1). Illinoian till; (2). Illinoian gumbotil; (3). Sangamon loesslike silt; (4). Old soil (Sangamon); (5). Peorian loess; (6). Shelbyville till; (7). Bloomington gravel; (8). Post-Bloomington loess.

small stream swings against the south valley wall at this place and undercuts actively enough to keep the face of the exposure fairly clean. At the time of visit the face was somewhat freer of slump than it was when the photograph previously referred to was taken.

DIMENSIONS AND FORM

The cut is about 100 feet high, 225 feet long in an east-west direction, and, with the exception of minor details, it still has about the same form as shown in Dr. Calvin's photograph. The general form and sequence of materials is sketched in the accompanying diagram (Fig. 1).

STRATIGRAPHIC SECTION

The following stratigraphic section is shown:

Post-Bloomington:

	Feet
8*c*. Soil, light gray, loessial	1– 1½
8*b*. Leached loess, brown, jointed by roots and surface weathering, thickness about	3½
8*a*. Calcareous loess, yellow, no shells found, thickness	0– 2½

Wisconsin gravel and till:

7. Bloomington gravel, discontinuous, brown, limestone pebbles present beneath calcareous loess, absent for a few inches directly beneath leached loess, thickness	0– 4
6. Shelbyville till, typical pebbly clay till with lens of gravel 8–10 feet thick on east side and about 10 feet below the top, the gravel contains till balls; till oxidized yellow in upper 2–6 feet with very faint maroon or orange tinge, bluish-gray below where damp, light-gray on dry surface, with slight maroon tinge, calcareous, thickness	32

Peorian:

5. Loess, grayish yellow, with rusty streaks and spots, fossiliferous, shells fragile and larger ones crushed and difficult to extricate, cleavage planes through the loess made by the pressure which crushed the shells, calcareous throughout, humus streak 2 inches thick about 10 inches below the Wisconsin till, contact with Wisconsin till sharp, thickness	6

Sangamon:

4. Old soil, dark with flakes of carbon, some fragments of old wood in east part of cut, loessial in texture, non-calcareous	1– 1½
3. Loesslike silt; on east side brownish in upper 1–1½ feet, grading below into grayish-yellow, 2–2½ feet, and again into brownish with carbon specks, 3–4 feet, the lower 2 feet showing slight trace of effervescence with acid; no effervescence in upper 5½ feet; no bedding or stratification. On west side this loesslike silt is bluish-gray with greenish cast below the old soil, the soil and about 6 inches of the greenish loess is leached; calcareous below, very compact, no bedding or stratification, scattered small pebbles in lower 3 feet; thickness same on both sides of cut	7– 8

Illinoian:

2. Gumbotil, chocolate brown, with reddish specks on east side, brownish to brick red at top with bluish-green spots on west side, tenacious, hackly fracture, siliceous pebbles, mostly under ¾ inch, non-calcareous, shear zones on west side, thickness about	4

Grades into:

1. Very calcareous till, few small lime concretions at top, limestone pebbles prevalent, grayish, mostly covered with wash and slump to base of cut..... 41

INTERPRETATIONS

Several important points are to be noted in the interpretation of this section.

1. There can be scarcely any doubt that the lower till is Illinoian in age. The typical Illinoian till occurs but a few miles to the south and southwest, with its surface at essentially the same elevation as it is here and with similar relations to the overlying loess.

South of the Wisconsin drift boundary, gumbotil has been found at the top of the Illinoian, and it is impressive to find it here. As pointed out by Kay and Pearce,[1] this peculiar tenacious, leached, and siliceous pebbly clay appears to be the product of a long interval of chemical weathering of the till before the deposition of the overlying deposit.

2. The overlying loesslike silt, horizon 3 of the section, seems best interpreted as a weathered loess. The color and weathered character of the Illinoian gumbotil below, and the thickness and calcareous content of the loesslike silt above, exclude the interpretation that the latter is the product of extreme weathering of the gumbotil. The occurrence of rare pebbles in the lower part is not unusual to the basal portion of any loess deposit which rests on a pebbly formation from which pebbles could be introduced secondarily by organic agencies. The calcareousness of the lower part of this deposit, although not notable, indicates that it was deposited subsequent to the weathering of the gumbotil. The upper leached zone of $5\frac{1}{2}$ feet, the brownish color on the east side of the cut, and the overlying old soil shows that this loesslike silt was subjected to subaerial agencies of weathering and plant growth for a considerable period before the deposition of the overlying fossiliferous loess.

The presence of this soil zone and the loesslike clay beneath the fossiliferous loess has not been hitherto noted in this exposure. In

[1] G. F. Kay and J. Newton Pearce, "The Origin of Gumbotil," *Jour. Geol.*, Vol. XXVIII (1920), pp. 89–125.

the legend of the photograph of the Farm Creek section in Monograph XXXVIII, Plate XI, Leverett includes all of the deposits between the Illinoian till and the Wisconsin till as "Iowan loess."

In the railway cut, one-half mile to the east, Leverett reports and illustrates by photograph the occurrence of a peat bed 3–5 feet thick, below the so-called "Iowan loess," and a 2- to 5-foot bed of silt between the peat bed and the underlying Illinoian till.[1] Of the silt Leverett states that it "bears some resemblance to the overlying Iowan loess in texture, but is not so calcareous and is of a deeper brown color. Whether it is similar in origin to the loess can scarcely be decided." Parenthetically, it may be stated that this monograph was written when the theory of the origin of the loess was swinging from the aqueous hypothesis to the eolian hypothesis, and the discussion carries the spirit of compromise rather than the present general view that the loess is dominantly eolian in origin.

The peat of the railway cut occupies the same horizon as the old soil in the Farm Creek exposure. The peat here, as Leverett points out, records poor drainage conditions after the weathering of the underlying till. It may well have been a local marsh, such as might result if there were relatively slight irregularities in the deposition of the loess on a previous flat surface. The Farm Creek exposure emphasizes the local transition that existed within short distances from subsurface drainage of an oxidizing character to nearly stagnant drainage of either unoxidizing or deoxidizing character. The brown to grayish-yellow color of the old loesslike silt in the east part of the cut is believed to represent the former condition, and the bluish-gray loesslike silt with greenish cast in the west part represents the latter. The difference in color of this loesslike silt and the normal loess is, therefore, not significant of a difference in mode of origin.

The overlying soil was formed subsequent to the deposition of the underlying loesslike silt, and before the deposition of the overlying loess. Whether its development represents the full period of time involved in the weathering of the underlying loesslike silt cannot be denied or affirmed. It represents at least the latter part of

[1] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey*, Monograph XXXVIII (1899), p. 128; Pl. XI *b*.

this period, and plausibly coincides with the Sangamon soils known elsewhere which are reported to contain boreal vegetable remains. Such vegetation probably lived during the transition from the Sangamon interglacial epoch to the Iowan glacial epoch, or even during the Iowan glacial epoch. There is, indeed, reason for thinking that the vegetable content of this soil and peat horizon represents the tundra conditions marginal to the Iowan ice sheet. The loesslike silt is referred to the latter part of the Sangamon, and the silt of Leverett's railroad section is correlated with it.

3. Horizon 5 is typical fossiliferous loess. A collection of shells was made and these have been identified by Curator F. C. Baker, of the Museum of Natural History of the University of Illinois, as *Helicina occulta* (Say), *Succinea ovales* (Say), and *Oreohelix iowensis*. The shells of the latter are crushed but identifiable. All three are common to the Peorian loess and the first two have been found in Recent loess. *Oreohelix iowensis*, according to Curator Baker, is not known in Recent loess. It is to be noted that the deposit is calcareous to the top, but the oxidized state, in contrast to the unoxidized basal portion of the Wisconsin drift, is in harmony with the evidence at other places that an interval of weathering occurred between the deposition of the loess and the overlying Shelbyville till. The Shelbyville ice may have removed the leached zone, as the contact of the loess with the Shelbyville till is sharp.

The 2-inch layer of humus which occurs 10 inches below the top of the loess records a cessation of wind deposition. Inasmuch as the writer does not recall any other exposure of Peorian loess—among the hundreds which he has seen—which shows a definite soil zone within the loess, he is inclined to the view that the soil represents the latter part of the Peorian epoch, and that the overlying 10 inches of loess was deposited during the oncoming of the Shelbyville ice. The alternative view is that this soil occurs within the body of the Peorian loess, recording two subepochs of loess deposition in the Peorian epoch, in which case there is the possibility that if there were a leached zone of the loess before the invasion of the early Wisconsin ice, that this zone and a part of the calcareous zone were removed by the ice. In a recent report on "The Iowan Drift—a Review of the Evidences of the Iowan Stage of Glaciation," Alden and Leighton

present the view that the great body of loess associated with the Iowan drift was deposited almost immediately following the recession of the Iowan ice sheet, but under sufficiently favorable climatic conditions to destroy the glacier and to permit the growth of vegetation and the existence of herbivorous snails;[1] in other words, the time of the loess deposition was referred to the early Peorian epoch.

If the first view outlined above is correct, the time of the deposition of the loess in the Farm Creek exposure is more closely connected with the Wisconsin glacial epoch than if the second view were found to be true. On the other hand, it is clear that the Peorian loess was deposited a long time after the deposition of the Illinoian drift.

4. The body of till at horizon 6 is unquestionably Early Wisconsin in age, and is clearly Shelbyville, since the Bloomington moraine lies to the north of this locality.

5. The overlying gravel is probably outwash from the Bloomington ice, since it occurs above the till and has an elevation in accord with the Bloomington outwash at Peoria.

6. The loess above the Shelbyville till and the Bloomington gravel is not mentioned in the legend accompanying the photograph in Monograph XXXVIII previously cited. Its thickness is from $4\frac{1}{2}$ to 7 feet. The upper $4\frac{1}{2}$ to 5 feet, including the soil, is non-calcareous, and where the non-calcareous portion rests on gravel, the gravel is partly leached. But where the loess is thicker than 5 feet its base is calcareous and the gravel beneath is unleached. This shows that at least a part, if not all, of the loess was deposited in a calcareous state immediately after the retreat of the ice at a rate in excess of leaching, and that subsequently the deposition of the loess either decreased in rate or ceased, giving opportunity for leaching to take place.

SUMMARY

This cut is remarkable in its display of evidence for two glacial epochs, the Illinoian and Wisconsin, and two interglacial epochs, the Sangamon and Peorian. Most of the varieties of interglacial evidence are present, including ordinary weathering, gumbotil develop-

[1] *Iowa Geol. Survey*, Vol. XXVI, "Annual Report for 1915," pp. 156–58.

ment, loess deposits, and soil formation. Not only is the common Peorian loess present, but also what seems to be loess of Sangamon age and the more-or-less local post-Wisconsin loess. Well deserving is the Farm Creek exposure—7 miles east of Peoria, Illinois—of a place among the type exposures of the Pleistocene of America.

The writer wishes to express his grateful appreciation to Curator F. C. Baker for his study of the fossils. His description of these is to be published soon.

PRE-ILLINOIAN TILL IN SOUTHERN ILLINOIS[1]

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ABSTRACT

In central Randolph County, southwestern Illinois, a 52-foot cut shows, below Illinoian drift, 12 feet of leached gray loess referred to Kansan time. Below this loess is a much-weathered old till, probably of Nebraskan age, which seems best attributed to ice invasion from the Labrador center.

INTRODUCTION

A section of glacial drift, showing undoubted pre-Illinoian till, of peculiar interest because of its location farther south than any

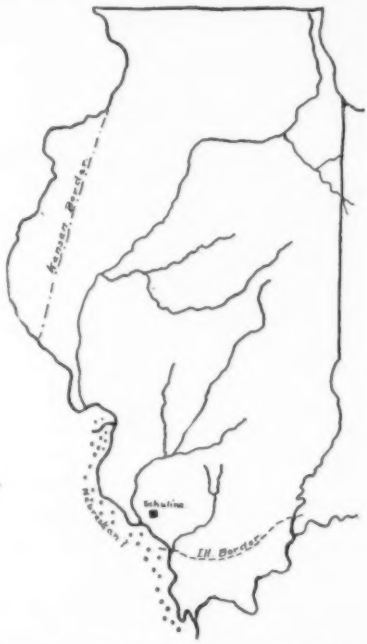

FIG. 1.—Index map of Illinois showing location of Schuline exposure

previously described pre-Illinoian till, was found in central Randolph County, Illinois, during the first season of Pleistocene studies in

[1] Published by permission of the chief of the Illinois State Geological Survey.

southern Illinois. Two miles west of the village of Schuline, a tributary to Little Plum Creek has undercut its west bank to make the exposure. The cut lies just south of the road in the north center of the NE. $\frac{1}{4}$, Sec. 24, T. 5 S., R. 7 W., Lat. 38°05′ N., and Long. 89°49′ W. (Fig. 1).

The topography of the vicinity is that of a monotonously flat till plain dissected by valleys 30–80 feet deep, many of which have small valley flats. The drainage pattern, typically dendritic, shows the valleys to be mainly post-Illinoian in their origin. The exposure was revisited by the writer in the company of Dr. M. M. Leighton, G. F. Moulton, R. M. Leggette, and W. Goddard, to whom thanks for helpful criticism and suggestion are given.

FIG. 2.—Schuline cut

TOPOGRAPHIC POSITION OF EXPOSURE

In the exposure, made by the stream's undercutting its west bank on the outside of a meander swing, glacial drift is exposed in a bluff 175 feet long and 52 feet high, so steep that footholds had to be cut in order to examine the details of the face (Fig. 2).

From the top of the cut, which is in a bit of a spur between the main and a tributary valley, the land surface slopes westward, away from the main valley. This topographic position is noteworthy, for it means that slumping could not have altered the original relations of the material.

TABLE I

DESCRIPTION OF THE MATERIAL (FIG. 3)

Section 1	Feet	Section 2	Feet
8. Loess	3–5	.....	
7. Gumbotil, Illinoian	2	.....	
6. Till, sand, and gravel leached	12	Till, leached	13
5.		Till, calcareous	3
		sandstone, cg	½
4. Loess, dense, leached	15	Loess leached	12–14
3.		Gumbotil	3
2. Till, leached	6–8	Till, leached	6
1. Till, calcareous	5½	Till, calcareous	5½

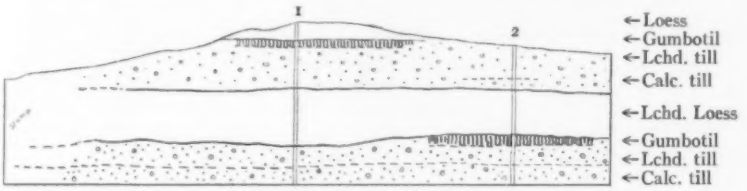

FIG. 3.—Diagram of the Schuline cut
Scale: ¼ inch = 10 feet

DESCRIPTIVE NOTES

8. The post-Illinoian loess is the typical light-buff, fine-textured loess of the southern part of the state.

7. Illinoian gumbotil is the typical dark bluish-gray, sticky, leached, and highly weathered surface of the Illinoian till.

6. The leached Illinoian till is fairly dense, dark yellow-brown, and stony, from which the lime content has been so removed by downward moving water that it does not effervesce with acid. Sand and gravel, also leached, are incorporated as lenses and pockets in the till.

5. In the northern part of the exposure (Sec. 2) the leached till grades almost imperceptibly downward into calcareous till, from which the lime carbonate has not yet been removed. This calcareous till is darker in color and somewhat more dense than the overlying drift. It shows also the fracture and texture of fresh till. At its base in one place 4 inches of sand and small pebbles have been cemented by lime into a fairly well-indurated conglomerate. In the southern part of the exposure (Sec. 1) the Illinoian till with the incorporated sand and gravel is leached to its base.

4. The 12–15-foot layer of dark brownish-gray loessial silt is entirely leached. Uniform in texture and composition from bottom to top, it fractures with characteristic loess faces and columns.

3. In the northern part of the cut (Sec. 2) the leached loess lies on a 3-foot horizon of brown-mottled, blue-gray, dense, sticky gumbotil. While not as well developed as the Illinoian gumbotil in this cut, it is nevertheless a very old soil zone and represents a long interval of weathering. In the southern part of the cut (Sec. 1) the gumbotil was eroded away before the loess (No. 4) was deposited.

2. The leached till is entirely oxidized to a yellow-brown color. It is fairly hard and medium stony. Stones up to 3 inches are not uncommon.

1. The calcareous till at the base of the cut is notable because of its hardness, compactness, and durability. The sharp pick must be driven with considerable force to dig into it. The mass is entirely oxidized to a yellow-brownish color, which is more pronounced along the many joints traversing it (Fig. 4). In the joints themselves, however, gray deoxidized color is seen. Along these joints, also, secondary lime has been deposited to so great an extent that erosion has left the joint filling projecting beyond the general surface (Fig. 4).

FIG. 4.—Photograph of jointing in lower till

This lower till contains not only many small polished and striated limestone pebbles, but also numerous cobbles and a few bowlders ranging in diameter up to a foot and a half. Sand and gravel lenses are also present. No purple quartzites were seen. A pebble count gives the percentage of materials shown in Table II. This shows a total of 13.2 per cent of foreign material.

It is not known definitely how thick the lower till is, but about 200 yards north of the exposure, a well at about the same elevation as the base of the cut penetrated 31 feet before encountering bed rock.

INTERPRETATION

The upper loess, while not fossiliferous in this place, bears such relations to the Illinoian drift that it is believed to be of early Peorian age. The Illinoian drift in its three phases, i.e., gumbotil, leached till, and fresh till, is normal and typical of the area.

Since the pre-Illinois loess formation was thoroughly leached prior to the invasion of the Illinoian ice, it must be notably older. And since it must have taken a long time to leach 15 feet of loess,

TABLE II

Limestone:		
Dense dark	14.3	
Soft (Pennsylvanian)	13.5	
Dense, few large crystals	2.3	
Crystalline	1.2	
Total		31.3
Chert		19.4
Sandstone (Pennsylvanian)		14.3
Ironstone concretions (Pennsylvanian)		10.0
Igneous rocks:		
Granite	4.0	
Greenstone	4.8	
Basalt	1.2	
Total		10.0
Lime concretions (Pleistocene)		8.0
White quartz pebbles (Pennsylvanian)		3.1
Shale (Pennsylvanian)		2.0
Quartzite (brownish and gray)		1.6
Quartz (white, crystalline)		0.4

assuming it to have been originally calcareous, a probable assumption in the case of loess, this formation seems to be associated with a pre-Illinoian glacial invasion—quite possibly the Kansan—as the early Peorian and early Wisconsin loesses are associated concomitantly with the late phases of the Iowan and early Wisconsin ice invasions, respectively. It could scarcely be associated in age or origin with the underlying till for it is separated therefrom by the gumbotil, and it is clearly not related to the gumbotil.

The lower till and gumbotil must be either Kansan or Nebraskan. Its relations to the leached gray loess above show that it is vastly older than the loess, for it was deposited, weathered to gumbotil,

and much of its upper surface eroded prior to the formation of the loess. It seems best, therefore, in the present state of the investigation to refer it to the earliest glaciation (Nebraskan).

Recent studies by Leverett and Schoewe (unpublished data) have shown a drift older and more extensive than the Kansan in Kansas and western Missouri. Pre-Illinoian drift is found in southeastern Missouri from St. Louis County southward to about the head of the gulf embayment. The occurrence of old till in St. Louis County has been discussed by Drushell[1] and Fenneman[2] and more recently noted by Shipton and Hanley, while farther south, erratics on the uplands have been noted by Shaw, M. Weller, Sauer, Flint, and Leverett. But in no place could the age of this older drift be definitely determined. In Illinois it has been described from the bluffs northwest of Alton,[3] but evidence in this case was not sufficient to determine whether the drift belongs to the Keewatin or the Labrador drift sheet. Leverett has described[4] pre-Illinoian drift in Monroe County where, west of Rock School (NE. ¼, Sec. 21, T. 3 S., R. 10 W.), he found 7 feet of much-indurated, massive till below 7 feet of softer Illinoian till. South of Burkesvill station (near the center of Sec. 20), a roadcut descending the hill showed a kaolinized soil zone at the top of the lower till. These exposures, however, are none too good, and their interpretation is consequently difficult. He is at present disposed to correlate this older drift with that found near Ste. Genevieve, Missouri, and to refer it to the earliest glaciation rather than to the Kansan.

With the evidence at hand of Labradorian pre-Illinoian drift in the La Salle and Hennepin[5] and Springfield[6] quadrangles in central Illinois, it is most plausible to include the pre-Illinoian drift near Schuline with that of the eastern ice-cap.

[1] *Jour. Geol.*, Vol. XVI (1908) pp. 493–98.

[2] "Geology and Mineral Resources of the St. Louis Quadrangle," *U.S. Geol. Survey, Bull. 438*, p. 31.

[3] M. M. Leighton, "The Pleistocene Succession near Alton Illinois," *Jour. Geol.*, Vol. XXIX (1921), pp. 505–14.

[4] Frank Leverett, personal communication, 1925.

[5] G. H. Cady, "Geology and Mineral Resources of the La Salle and Hennepin Quadrangles," *Bull. 37, Ill. State Geol. Survey* (1919), p. 71.

[6] E. W. Shaw and T. E. Savage, "The Tellula-Springfield Quadrangle," *U.S. Geol. Survey, Folio No. 188* (1913), p. 7.

A REVISED FIELD CLASSIFICATION OF IGNEOUS ROCKS

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ABSTRACT

This paper gives a revision of the author's "field" classification of igneous rocks, published in this *Journal* in 1911.

Some years ago the writer[1] published a paper on "Petrographic Terms for Field Use," in which he proposed slight changes in the spelling and pronunciation of a few common rock names. By these changes he wished to indicate that they were field terms, to be applied to rocks that had not been determined accurately under the microscope. The ending chosen was *-eid*, since it makes only a slight change in the English pronunciation; but the spelling gives an awkward appearance to the words. For the past ten years the author has used in his classes the ending *-ide*, as in "dioride," etc., the simple change from the *t* of the more accurate classification to the *d* in this indicating that the rock has been classified megascopically only. Besides this change in ending, he has made a few changes in rock names. It was originally his intention not to publish this revision until it appeared in a forthcoming textbook, but since the former classification has once more come on the scene in a paper by Scheumann,[2] it may be well to show the new names in tabular form (Table I).

The term "trappide" is substituted for the former "anameseid"

[1] Albert Johannsen, "Petrographic Terms for Field Use," *Jour. Geol.*, Vol. XIX (1911), pp. 317–22.

[2] K. H. Scheumann, "Ausländische Systematik, Klassifikation und Nomenklatur der Magmengesteine, I," *Fortschritte d. Min., Kristal., u. Petrog.*, Vol. X (1925), pp. 187–310.

Curiously enough, Scheumann says in a footnote (p. 252) in regard to the ending *-eid:* "Für die deutsche Sprache wäre die Endung *-id* zweckmässiger." The writer changed the spelling from *-eid* to *-ide* immediately after the appearance of a review by Wetzel (*Neues Jahrb.*, Vol. II (1913), pp. 237–38) in which the endings were written "graneid," "syeneid," "dioreid," etc.

for the sake of simplicity. Trapp is the old term used by geologists for an extrusive rock, non-porphyritic and dark colored. It was used as long ago as 1823 by von Leonhard in this sense.

"Perknide" is substituted for "pyriboleid," following Turner's use of perknite for the dark rocks of the peridotite and pyroxenite families.

TABLE I

	Ferromagnesian Minerals <50%		Ferromagnesian Minerals >50%		Neither Feldspar nor Quartz Is Present	
	+Quartz	−Quartz	−Quartz	−Quartz	−Quartz, −Olivine	−Quartz, +Olivine
Usual Ferromagnesian Mineral Is:	Biotite	Biotite or Amphibole	Amphibole	Pyroxene	Amphibole or Pyroxene	Olivine, Amphibole, or Pyroxene
Glasses	Pumice, obsidian, pitchstone, etc., etc.					
Porphyritic glasses	Vitrophyride					
Aphanides	Felside		Trappide			
Aphanide-porphyries	Leucophyride		Melanophyride			
Phanerides	Granide	Syenide	Dioride, Gabbride		Amphibolide Pyroxenide	Peridotide
					Perknide	

In many cases it is impossible to determine megascopically whether an amphibole or a pyroxene is present in the phanerides. For such rocks the word "dolereid" was used in the former classification. The term is very bad, however, since "dolerite" was originally applied to extrusive rocks. The term "greenstone" could properly be applied here, since Grünstein was originally used for rocks composed of feldspar and amphibole or pyroxene. (From this group the hornblende rocks were later separated by Hauy as diorites.) But greenstone is in such common use for altered rocks which may be extrusives that it is not advisable to use it. No name is suggested at present.

REVIEWS

Index to Paleontology (Geological Publications, 1847–1916). Compiled by FRANK NICOLAS, pp. 1–383, 1925, *Geological Survey*, Canada, Publication No. 2034. Price, 50 cents.

Captain Nicolas' index to the fossils recorded in the reports of the *Geological Survey of Canada* has furnished a long-needed key to the wealth of knowledge concerning ancient life which is widely scattered through these reports. A work of reference in many volumes without an index is about as useful as a twenty-story building without an elevator. Paleontologists will probably be sufficiently thankful for this great aid and ally which Captain Nicolas' persevering industry has placed in their hands to overlook any technical defects which they may discover in it.

Those who use this work will find in the supplementary list of specific names, which occupies sixty-five pages, a valuable adjunct to the Index. In it the several generic names which have been associated with each specific name follow it, and the accepted generic names appear in small capitals, while synonyms are in italics. A list of fossils whose specific and generic names have both been changed terminates the volume. This work should be welcomed by everyone interested in geology and, we believe, by a great number of biologists as well. Every biologist has some interest in paleontology—the *hinterland* or the historical background of his subject—and will have much occasion to use this index. The botanist will be able to find out with its help all that has been recorded concerning the Tertiary and Cretaceous ancestors of modern trees in the 180 volumes covered by the Index. The recorded information in this series of volumes concerning the geographical distribution of living shells during the Pleistocene becomes easily usable for the first time with the aid of the Index.

The writer hopes that the author of this Index will follow it with another which will cover scientific reports other than those of the *Geological Survey of Canada*, in which descriptions and references to Canadian fossils occur. In such a work the scope and plan of the present one should be improved upon by indicating the geological horizon of every species cited.

By way of illustrating the important rôle which fossils play in economic geology, it may be noted here that when the preliminary survey of New York State was completed, about eighty years ago, the geologists

announced that coal would never be found within the areas they had covered. This conclusion was based on the determination of the age of the New York rocks by means of fossils which indicated that the coal-measure rocks were absent from the state. Coal is still unknown in New York State, and one of the results of the geological surveys made there has been the prevention of the waste of large sums previously squandered annually in searching for coal at horizons below the Carboniferous.

Names of fossils before they can become entirely efficient allies of the structural or economic geologist and a part of the permanent fabric of science require interpretation in terms of time and space. The index is a most important step in this direction. The data which through many years have been accumulated by the labor of many men and have appeared under hundreds of titles become truly significant only when the range in time and the geographical distribution of each species can be shown. An index such as this is a very large contribution to such an objective.

In 1623 the Frenchman, Gabriel Sagard-Theodat, commonly called Sagard, of the Recollet order, in company with two other followers of the great nature lover, St. Francis of Assisi, ascended the Ottawa River and observed, in passing the Chaudiere Falls opposite the present city of Ottawa, that the rocks were covered with what seemed to be small stone snails (*petits limas en pierre*). Sagard records concerning these: "I am unable to account for this, unless it is owing to the nature of the stone itself, or that the result has been produced by mist from the falling waters" (*Grand Voyage du Pays des Hurons*, 1632). It is a far cry from this first published reference to Canadian fossils three centuries ago to the recently published 383-page check list of the fossils of Canada.

When the history of the development of a systematic knowledge of the ancient life of Canada is written, a century or two hence, the mist-made fossils of the keen-eyed Frenchman will be the recognized starting-point, and Captain Nicolas' Index one of the conspicuous milestones on the great highway of Canadian paleontology.

E. M. KINDLE

Gems and Gem Materials. By E. H. KRAUS and E. F. HOLDEN. New York: McGraw-Hill Book Co., 1925. Pp. 222. $3.00.

This work, written especially for jewelers, closely resembles a text-book. Introductory chapters, covering 104 pages, on crystal, physical, optical, and chemical properties, and on the origin, cutting, naming, and manufacturing of gems lead up to an eighty-page section briefly describ-

ing sixty-four gem materials. Ten tables listing gem materials by various properties, and a summary table of eighteen pages with alphabetical arrangement, complete the work.

In the brief space given to optical properties (26 pages) it seems that the authors attempt to cover too large a part of this field. The old idea that igneous rocks form from fusions by solidification of molten magmas is given on page 63. On page 64 vesuvianite is given as an example of a mineral formed by regional metamorphism; on page 170 the statement, "vesuvianite is a contact metamorphic mineral" appears. On page 144 it is stated that "quartz is the most common mineral in the earth's crust."

The simplest possible terms are used in the descriptions of the gem materials. Two hundred and fifty-six excellent illustrations greatly enhance the appearance of the work. Only a dozen or so typographical errors were noted. Twenty-nine pages used to describe the cutting, polishing, and manufacturing of gems are of considerable interest. It is quite the finest book, covering gems, available at so low a price.

D. J. F.

Interpretation of Topographic and Geologic Maps. By C. L. DAKE and J. S. BROWN. New York: McGraw-Hill Book Co., 1925. Pp. xi+355; figs., 52. $3.00.

Treating almost every recognized phase of map interpretation, the authors have contributed a well-written volume which will surely prove useful to those studying earth forms and structures. The book is conveniently divided into two parts, the first dealing with topographic maps, and the second with geologic maps. There are no chapter divisions; the major subjects are subdivided under topical headlines. Under each topical division are listed the available maps of the United States Geological Survey which illustrate the phenomena under consideration. Following the map list is an illuminating discussion of the various quadrangles, in which the authors designate in italics and bring out clearly the geological features under consideration; they point out to the student the maps on which these are best illustrated. Supplementing this are many short general discussions of geological principles, and a statement of the geographic distribution of the topographic and structural features. A number of new and little-used terms are defined, such as "neutral shoreline," "nip," "fine- and coarse-textured topography," "barbed tributary," "flatiron, etc." For the most part the illustrations are simple line drawings, of which there are very few in Part I.

Part I begins with an explanation of the principles upon which geologic maps are constructed. This is followed by an elucidating discussion of various map scales, methods of representing topography, and the significance of contours. Then in succession are taken up the topographic features resulting from the various earth processes. Toward the end the discussions deal with the relations of certain land forms to rock structures.

Part II, dealing with geologic maps, forms the most valuable portion of the volume. The map lists are supplemented with numerous block diagrams illustrating structures and geometric figures for the solution of structural problems. There are topical treatments of various kinds of dipping beds, folds, faults, igneous structures, and unconformities. The explanations of depth-line maps, hydrologic maps, and contours on unconformities are subjects which are distinctly new in a treatise of this character. The treatment of faulted and dipping beds is the most valuable contribution of the authors. An appendix following each part gives an alphabetical list of the geologic maps studied.

D. G.

Elements of Geology. By T. T. QUIRKE. New York: Henry Holt and Co., 1925. Pp. 414, pls. 102. $3.50.

This volume is a textbook which is prepared to accompany a beginning course in general geology covering a period of sixteen weeks, with classroom and laboratory exercises of five hours per week. It is designed particularly for students of general engineering and agriculture. The mechanical features of the volume are excellent. It is well printed on good paper with clear type, and is well illustrated. A large number of its halftones have not appeared before in print.

The chief value of the text lies in the method of its approach to the subjects that are treated. The author utilizes very thoroughly the examples of those geological phenomena with which the beginning student is most likely to be familiar.

The book is divided into four parts: the earth, geologic processes, historical geology, and laboratory exercises. The first part includes a chapter on the earth as a planet, and another on the earth's crust. The first chapter will be appreciated by second- and third-year students of engineering, but the Freshman who has had little mathematical training is likely to find it rough sledding, for the mathematical treatment is more technical than that found in most texts that are prepared for more advanced students. The second chapter, which treats of the earth's crust,

is brief, but it is clear and, supported by the laboratory exercises outlined in Part IV, it will provide a sufficiently comprehensive outline of the composition and origin of the materials of which the earth's crust is composed.

Part II, which treats of geologic processes, is the major section of the volume. It includes 236 pages and is supported by the larger part of the laboratory exercises. Chapter headings are: "Erosion and Restoration," "The Atmosphere," "Land Waters," "The Sea," "Glaciers," "Vulcanism," "Diastrophism," and "The Interrelation of Earth Processes." It is in this section that the author's method is most evident—that of utilizing the student's experience to illustrate the processes treated. This method, which all will admit is good practice, is likely to result in an ill-balanced treatment unless skilfully used. One sees little evidence of ill-balance, however, in this section of the book if he keeps in mind the purpose for which the volume is written. The longest chapter is the one treating land waters. That is warranted perhaps in any general text on geology, but particularly in one prepared for engineering students.

Part III treats of historical geology. This part, which is only about forty pages long, covers very briefly the history of the earth, from its beginning as part of a spiral nebula to the present day.

The book contains no references. These are omitted for brevity. In the opinion of the reviewer, even the most elementary text should be supplied with at least a small number of selected references. They add a personal interest to the subject treated; they give the writer an opportunity to point to the sources of his material, and they show the way to the student who wishes to pursue the subject farther.

Part IV of the volume includes a group of laboratory exercises and embraces altogether about eighty-two pages. The first three exercises treat of the common minerals and rocks. The fourth exercise treats of the distribution and occurrence of igneous and sedimentary rocks in two selected areas. Exercise 5 is an introduction to the study of topographic maps. In the exercises following, a number of selected topographic and geologic maps are described. These are succeeded by outlines for the study of other maps which, by the question-and-answer method, are intended to familiarize the student with the method of using maps and with the topography and geology of certain areas. These exercises are well worked out and constitute one of the chief contributions of the volume.

The book will serve a useful purpose in its somewhat specialized field, and is a valuable contribution to the list of geologic texts.

W. H. EMMONS

Retreat of the Last Ice-Sheet from Eastern Canada. By ERNST ANTEVS. Ottawa: Canadian Geological Survey, Memoir 146, 1925. Pp. 138, pls. 9, figs. 27, maps 10. $0.25.

Dr. Ernst Antevs, of the University of Stockholm, came to America with Baron Gerard DeGeer's party in the summer of 1920. Since then he has carried on extensive work in connection with the retreat of the last ice-sheet.

His first work in this country was done with the varved clays of the Connecticut Valley. This present memoir is the result of the extension of this study northward into eastern Ontario and Quebec. It contains by far the best and most detailed discussion of these very interesting sediments that has yet appeared in English. The characteristics and uses of these annually banded clays were first studied by DeGeer, working in Sweden and Norway.

Dr. Antevs does not claim too much for this new method. He points out clearly that while these clays, as yet, form the basis for the only exact geochronology during and since the retreat of the last ice-sheet, there are many limitations in their use, especially for distant correlation; and that in attempting to correlate and date the events of this retreat it is necessary to use the larger features before applying this new, more exact, method. Thus, in his summary of the events in the withdrawal of the ice from the Ontario peninsula he uses Spencer's and Taylor's estimates of the time involved, made from their studies of the recession of Niagara Falls. He also uses Coleman's estimates made from his studies of glacial-lake beaches, and similar criteria. Dr. Antevs points out, for use in this connection, the importance of tracing laterally the terminal and recessional moraines, as has been done recently by Taylor, in the St. Lawrence Valley.

Among some of the many good features of the work might also be mentioned the extensive bibliography of the subject, and the large number of figures, maps, and graphs. He gives in their entirety the normal curves, or thermal graphs, for the numerous localities in which he worked, thus making ali his data available for future students of the problem.

Probably the most valuable feature of this memoir is that it points the way to a method for obtaining an exact history of the retreat of the last ice-sheet in eastern North America. This is probably necessary before any attempt is made to correlate accurately the late glacial events of this continent with those of Northwestern Europe, or to connect glacial with historical time.

W. W. W.

Quantitative Standards for Hardness of the Ore Minerals. By STERLING B. TALMAGE. Economic Geology, Vol. XX, No. 6, September–October, 1925, pp. 531–53.

A new instrument of remarkable sensitiveness has been perfected by Professor Talmage for the determination of the hardness of minerals. By it accurate determinations may be made on specimens no larger than a pin-head, the length of the scratch being less than a millimeter. The scratching is done with a cut-diamond edge on the polished surface of a mineral which is fixed to the stage of a microscope. The diamond edge is at one end of a very sensitive balance. By manipulation of the weights the width of the scratch may be varied at will. For the softer minerals a weight of about one-tenth of one gram is sufficient and for the harder, a weight of about one and one-half grams is necessary.

So far, the investigator has applied the instrument only to the ore minerals, and includes in his discussion a new table of 150 of the ore minerals, divided into seven convenient groups, and arranged in the order of their hardness. He lists argentite as the standard mineral for the softest of these groups, and ilmenite as the standard mineral for the hardest. The new table probably exceeds all others in accuracy, and the instrument will be of additional value in determining the hardness of metals and alloys.

D. G.

Useful Aspects of Geology. By S. J. SHAND, Professor of Geology in the University of Stellenbosch, South Africa. London: Thomas Murby & Co., 1925. Pp. x+197; figs., 23.

In this small volume a variety of geological topics are treated by a South African geologist in a manner quite different from that most familiar to American readers. The first chapter is an introduction to the study of rock structure, classification, and origin. Following in succession are chapters on various economic phases, such as oil geology, mineral deposits, and building-stones; other chapters treat rock-weathering, vulcanism, structure, and metamorphism; the concluding chapter applies geology to the common problems of engineering. Although the book is written for the "large class of people who have never picked up any systematic knowledge of geology," it seems to the reviewer that the unversed person may perhaps find it a bit technical, even though it was the professed purpose of the author to avoid such treatment.

D. G.

A Textbook of Geology (2d ed., revised). Part II. *Historical Geology*. By CHARLES SCHUCHERT. New York: John Wiley and Sons, 1924. Pp. 724, 237 figs. and 47 plates.

Professor Schuchert's *Historical Geology* has come to be one of the widely used textbooks in the colleges and universities of America. All teachers of the subject at least use it as a work of reference, and in many places it is the designated text for college classes in historical geology. No book could come to be so widely recognized unless it possessed many admirable qualities.

The second edition of this popular text has now been in service for more than a year. In its make-up the plan of the earlier edition has been closely followed, but with some rearrangement of materials, and additional material has been incorporated to the extent of about one hundred more pages. These additional pages are occupied in part by new material which has become available since 1915, the date of publication of the earlier edition, and in part by further elucidation of materials which were included in the first edition.

It is easy to recognize that the book has been written by one thoroughly versed in the subject of paleontology. The main features of the introduction and succession of life-forms are admirably set forth in the chapters devoted to these topics. The discussion of the general characteristics of the several classes of invertebrate animals in connection with the time periods when they became conspicuous elements in the faunas is a method of presentation which is helpful to the student and to the general reader. The introduction of portraits of eminent geologists from time to time, in those chapters where the work of these men stands forth, adds greatly to the interest of the user of the book. The introduction of numerous carefully thought-out paleogeographic maps brings out facts relating to the geographic distribution of the ancient faunas as no other method could do.

The most serious criticism of the book is found in the failure of the author to discuss as fully as he might the interpretation of geologic facts which are at variance with the views which he himself holds. Very many geologic phenomena are capable of interpretation in more than one way, and where a single interpretation is presented in a more or less dogmatic manner, students are misled into believing that such interpretation has been fully established. In order to develop the true scientific attitude of mind in students of college or university grade, for whom the book is written, the several interpretations should be presented so that the student may exercise his own powers of reasoning and judgment.

In the book the existence of east-west trending continents throughout

the earlier geologic periods, and the change to the existing north-south trending continents in comparatively recent geologic time, is reiterated over and over again. This whole interpretation is associated with the recognition of an ancient continent, Gondwana Land, stretching from Australia and India through Africa to South America. It is safe to say that many, perhaps, most American geologists do not consider that the existence of this continent has been established, since it seems to do violence to various geologic facts. The dynamics associated with the rather abrupt submergence of a large portion of an emergent continent to abysmal oceanic depths are difficult to conceive. It is also a well-established fact that in existent continents their structural grain more or less parallels their borders, and this grain has repeated itself over and over again from very early geologic time. Such is not the case in the hypothetical Gondwana Land. The only real basis for assuming the existence of such a continent is found in the distribution of certain ancient glacial deposits and of certain organisms in the past, notably the *Glossopteris* flora. To many geologists it seems that the distribution of this flora and other organic distributions can as well be accounted for by connections between our existing continents and Antarctica, without doing such great violation to the earth dynamics.

Another example of the same sort is the division of the Mississippian Period into the Waverlian and the Tennesseean, a classification which is in no respect in accord with the Mississippian stratigraphy and paleontology of the standard Mississippian section, and yet the user of the book could only infer that this classification was fully established.

Notwithstanding such faults as have been mentioned, the book remains a most useful contribution to geologic literature. It is clearly written, well illustrated, and admirably arranged. It is so readable that it cannot fail to be sought after by the layman, as well as by the student and the professional geologist.

S. W.

Fourteenth Annual Report of the State Geologist of Vermont. By GEORGE H. PERKINS, state geologist. Burlington, Vermont: Free Press Printing Co., 1924. Pp. 351+x, 7 figs., 25 plates.

Including a number of studies which are of general value to geology as well as to the geology of Vermont, the fourteenth report of the *Survey* forms an important addition to the systematic interpretation of the geology of a state with a multiplicity of difficult problems.

Percy Raymond describes a coral reef in the top beds of the Lower

Chazy formation of the Isle la Motte, which he thinks is the oldest coral reef in the world. It is part of a narrow strip of rocks in the western part of the state which escaped the intense metamorphism which affected the surrounding region. He describes most of the corals as similar to Favosites in habit, but showing lateral, instead of calicinal, gemmation. This has led him to form a new genus, *Lamottia*. He includes a description and illustrations of the new species, *Lamottia heroensis*. The same investigator describes a number of new trilobites which were found in the Upper Cambrian of northwestern Vermont by Schuchert and his assistants. Of the forty-five species described, thirty-six are new.

The Cambrian succession in northwestern Vermont is described by Keith, who has established a geologic succession from the Lower Cambrian to the Middle Ordovician. At the base is the Monkton quartzite; then, in succession, follow the Mallett dolomite, Highgate slate, Sherburne marble, Williston limestone, Swanton conglomerate, and the Georgia slate.

The geology of Grand Island County is presented by the state geologist, Professor Perkins. The rocks which the *Survey* formerly considered as Utica in age, he now includes as part of the Upper Trenton. Other formations which are exposed in the area are the Lower Trenton, Black River, Chazy, and Beekmantown.

The second of a series of papers on the geology of an area of about one hundred square miles, in the Champlain Valley of Vermont, by Edward Foyles, gives evidence for believing that the rocks in the vicinity of Fort Cassin are not Beekmantown in age, but are equivalent to the Chazy and the Black River formations.

D. G.